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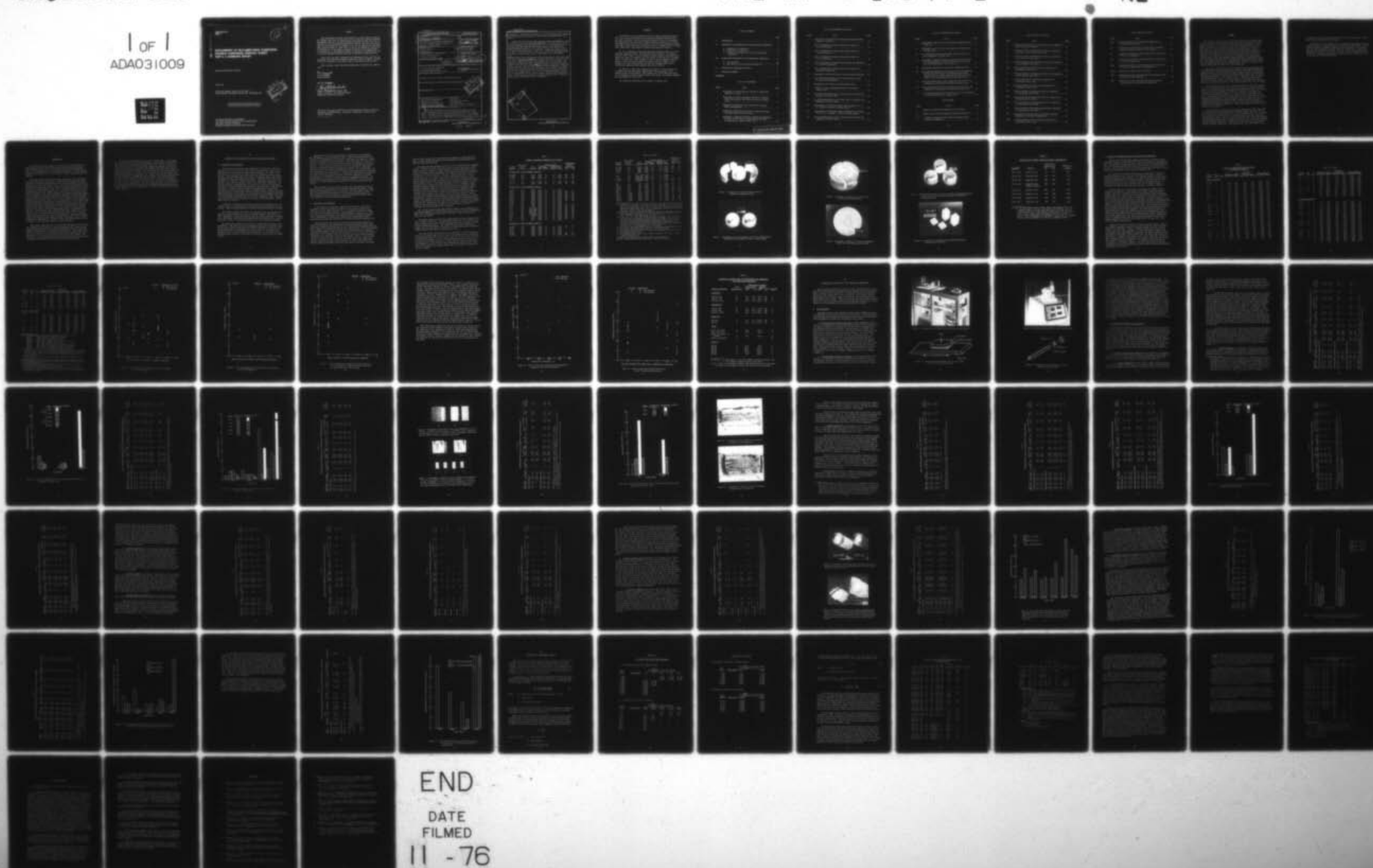

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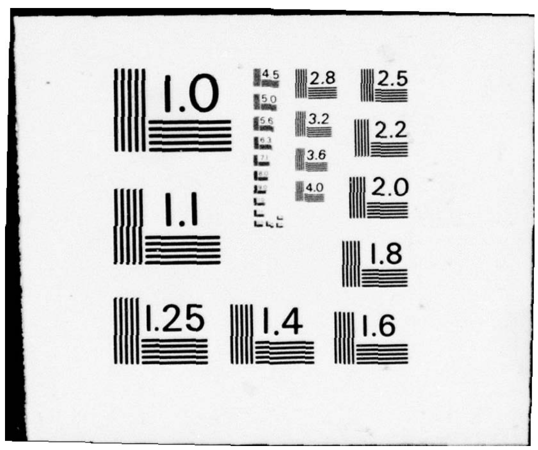
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AFML-TR-75-175
PART II

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DEVELOPMENT OF SELF-LUBRICATING COMPOSITES UTILIZING CARBONIZED PHENOLIC MATRIX PART II, A SUMMARY REPORT

MIDWEST RESEARCH INSTITUTE

APRIL 1976

TECHNICAL REPORT AFML-TR-75-175, PART II
FINAL REPORT FOR PERIOD AUGUST 1975 - DECEMBER 1975

AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This technical report has been reviewed and is approved for publication.

B. D. McConnell

B. D. McCONNELL
Project Monitor

FOR THE COMMANDER

Larry L. Fehrenbacher

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1. REPORT NUMBER 18 AFML-TR-75-175, Part ~~II~~ 2 — 2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER 9
4. TITLE (and Subtitle) 6 DEVELOPMENT OF SELF-LUBRICATING COMPOSITES UTILIZING CARBONIZED PHENOLIC MATRIX. PART II. A SUMMARY REPORT.	5. TYPE OF REPORT & PERIOD COVERED Final Technical Report, 1 Aug [redacted] 31 Dec 75
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 Melvin T. Lavik, Vern Hopkins	8. CONTRACT OR GRANT NUMBER(s) 15 F33615-75-C-5101
9. PERFORMING ORGANIZATION NAME AND ADDRESS Midwest Research Institute, 425 Volker Boulevard, Kansas City, Missouri 64110	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 17 73430206 16 AF-7343
11. CONTROLLING OFFICE NAME AND ADDRESS 12 86p.	12. REPORT DATE 11 Apr[redacted]976 MRI-4014-E
	13. NUMBER OF PAGES 74
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio 45433	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

AD A020 951

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Carbon Fiber Reinforcement
Carbonized Resin Matrix
Composites, Self-Lubricating
Composites, Fiber Reinforced
Friction and Wear Measurement
Lubrication
Oscillatory Wear Testers
Solid Lubricants
Wear Factor, Material Comparison

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Exploratory development and evaluation has been conducted on self-lubricating composites which utilize a carbonized phenolic resin (CPR) matrix. Composites have been prepared with as much as 59% (vol.) graphite fibers. Specimens have been compression-molded directly as journal liners within a metal housing or as blanks which can be machined into desired test

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configurations. Additives such as Sb_2O_3, ZnO, and tetrafluoroethylene powders have provided beneficial synergistic effects within the CPR-MoS_2-fiber composites.

Screening friction and wear tests have been conducted at various loads from 1,500 to 27,450 psi (10.3 to 189 MN/m^2) and speeds from 3 to 36 fpm (0.015 to 0.152 m/s). The composites with approximately 30 vol % fiber performed better at the high loads than those with lower fiber content. Small quantities of tetrafluoroethylene powder (2 vol %) effected a lower, more steady friction coefficient while maintaining a low wear rate. Linear wear factors as low as 4×10^{-8} in. of wear per foot of travel (3.3×10^{-9} m/m) were measured at the high load, the specific wear factor is approximately 4.1×10^{-17} m^3/Nm.

Oscillatory journal bearing tests have been conducted at loads from 2,000 to 12,000 psi (13.8 to 83 MN/m^2) at an average linear speed of 2.18 fpm (0.011 m/s) and at temperatures of 100, 400, and 600°F (311, 477, and 588°K). The composites containing 31% fibers exhibited much better wear resistance than composites with 18% fiber content. The wear factors of the better composites tended to decrease with increasing load and increasing temperature. Although the specific wear factors are higher by factors of 10 to 400 in oscillating journal tests than in flat-on-flat oscillatory tests, the radial wear (1.0 to 11.5×10^{-4} in/25,000 cycles; 2.5 to 29.2×10^{-6} m/25,000 cycles) is within the stated acceptable wear for control surface bearings in high load applications. Further testing is required to determine the load limit of these composites within the PV values used in current tests.

FOREWORD

The purpose of this program has been to conduct exploratory development work on new and improved self-lubricating composite materials and processes consistent with current and anticipated Air Force requirements. The program has been conducted at Midwest Research Institute, 425 Volker Boulevard, Kansas City, Missouri 64110, for the Air Force Materials Laboratory (MBT), under Contract No. F33615-75-C-5101 (1 December 1974 to 31 March 1976), Project No. 7343, Task No. 734302, MRI Project No. 4014-E.

Mr. B. D. McConnell of the Lubricants and Tribology Branch, Air Force Materials Laboratory (MBT), has been the Project Engineer. An interim contract report, Part I, of the summary technical report, was submitted in August and issued in December 1975, and covered the period from 1 December 1974 to 31 July 1975. This document is Part II of the summary technical report, covering the work conducted during the period 1 August to 31 December 1975, and contains friction, wear and strength data on self-lubricating composites which augment that given in Part I.

Mr. Melvin T. Lavik, who prepared this report, is the principal investigator and has the overall responsibility of the program. He is assisted by Mr. William Walker, who conducts most of the laboratory work. Mr. Vern Hopkins provides overall guidance and assists in specific planning and coordination of activities.

The report was submitted by the authors in January 1976.

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SUMMARY

This program, conducted for the Air Force Materials Laboratory, has been concerned with the development and evaluation of improved self-lubricating composites. The concept of utilizing carbonized phenolic resin (CPR) as a matrix for lubricating pigments was developed on an earlier AFML contract. The potential advantages of the CPR system include: (1) almost unlimited formulation possibilities because of the material compatibility with phenolic; (2) the processing design by which hardness, stiffness, and temperature stability can be adjusted; and (3) the low material cost. Early development efforts resulted in two formulations which functioned very well in room temperature tests at loads up to 3,000 psi (20.7 MN/m^2) and speeds up to 588 fpm (2.99 m/s) wherein the PV did not exceed 108,000 lb-ft/in^2-min (3.78 MNm/m^2-sec). However, at higher loads, fiber reinforcement was found to be very beneficial.

During this report period, numerous specimens have been prepared with modified compositions and processing techniques. CPR composites have been prepared with 18, 31, 38, 44 and 59% (vol.) graphite fibers. Synergistic additives included with MoS_2 and the fibers include Sb_2O_3, ZnO, and tetrafluoroethylene powders. Specimens have been compression-molded as blanks for machining into slider or journal sleeves; others have been formed directly as journal sleeves in a metal housing. Specimens have been carbonized at maximum temperatures of 320, 400 and 550°C (593, 673, and 823°K).

The CPR composites have been evaluated for friction and wear characteristics in screening tests of flat specimens sliding in oscillatory motion and in real journal bearings operating in the oscillatory mode. The screening tests have been conducted at loads from 1,500 psi (10.3 MN/m^2) to 27,000 psi (189 MN/m^2) and speeds of 3 fpm (0.015 m/s) to 36 fpm (0.152 m/s). Specimens containing 30 to 38% graphite fibers performed very well in these screening tests. The synergistic additive, Sb_2O_3, alone or in combination with tetrafluoroethylene powder (within the fiber reinforced MoS_2-based CPR composite) appear to offer the best friction and wear performance under these test conditions. These data compare favorably to data cited in the literature.

The oscillatory journal tests have been conducted at loads from 2,000 to 12,000 psi (13.8 to 82.7 MN/m^2) at an average linear speed of 2.18 fpm (0.011 m/s) and at temperatures of 100, 400, and 600°F (311, 477 and 588°K). The specimens containing 31% fibers exhibited much lower wear than those containing 18% fibers. The wear factors decreased with increasing load and with increasing temperatures. Comparison of these data with values reported in the literature indicate the friction and wear values of these CPR composites are very competitive. The wear and friction values appear to be

acceptable for many Air Force applications at the PV factor used in these tests, which were accelerated in speed.

Evaluation of these composites at the desired design conditions, which includes speeds of 11 cpm and loads up to 40,000 psi (276 MN/m^2), has been greatly limited by alignment problems on the test machine. In the tests that have been conducted at 11 cpm (0.25 fpm; 0.00122 m/s), failure has occurred at 8,000 psi (55.2 MN/m^2). However, in each test there was some indication of alignment problems which caused excessive loading to occur at one edge of the journal bearing.

I.

INTRODUCTION

The objective of the program is to develop new and improved self-lubricating composite materials with high-load and high-temperature (600°F; 588°K) capabilities. Materials developed here are expected to serve as a technology base for development of specific self-lubricating bearing liner materials for use in aircraft control and landing gear components.

Self-lubricating composites have been the subject of investigation for many years and by many workers. Many plastic materials have been found to be effective as bearing materials with no external lubrication, especially at light loads (Refs. 1-3). The load carrying capacity can be substantially increased with the inclusion of high-strength fibers, such as glass or carbon/graphite (Refs. 4-8). Similarly the friction coefficient and wear rate can frequently be reduced by the inclusion of solid lubricant powders, such as MoS_2, graphite, and tetrafluoroethylene (Refs. 9-11). Another class of self-lubricating composites has been developed by the formation of a refractory metal matrix for MoS_2 or other thermally stable solid lubricants (Refs. 12,13). These composites are formed under moderate pressures by sintering at high temperatures. Still another class of self-lubricating composite has recently been investigated. This patented concept (Ref. 14) has been to utilize the structure of selected resins, after partial carbonization, as the matrix for solid lubricant pigments. The results of prior development efforts in developing this last class of self-lubricating composites have been summarized in prior reports to the Air Force Materials Laboratory (Refs. 15,16). Phenolic resin has been selected for initial investigation. Lubricating pigments of MoS_2 and Sb_2O_3 have been effective within the phenolic resin, either carbonized or uncarbonized. Graphite fibers have proven effective in increasing the load carrying capacity of these composites.

The current effort has been to extend the development of solid lubricant composites which utilize a carbonized phenolic resin matrix. The primary thrust has been the inclusion of greater quantities of graphite fibers for improvement of the high-load performance. Solid lubricating materials developed on this program and the earlier programs have been evaluated and applications for these materials have been sought. The development and evaluation efforts have been directed toward the solution of current and anticipated Air Force lubrication problem areas.

The work performed during the period of 1 August 1975 to 31 December 1975 is described in the following sections of this report. Much of the data collected in the period 1 December 1974 to 31 July 1975 is also included in this report for reference and comparison purposes. The next section, dealing with the preparation and formulation of self-lubricating composites, discusses procedures used in mixing, molding, carbonizing, and fabricating composite materials. Also discussed are the synergistic and reinforcement additives, specimen sizes, weight losses during carbonization, and the evaluation of compression test specimens. The following section deals with the tribological evaluation of these experimental composites. The test machines and procedures are discussed, followed by presentation of the data for each composition. The next section presents a discussion of the experimental results obtained on this program and compares them with recent results found in the literature. The final section consists of concluding comments.

II.

FORMULATION AND PREPARATION OF SELF-LUBRICATING COMPOSITES

A. Preparation of Composites

Prior work has resulted in the development of partially carbonized phenolic resin as a matrix for self-lubricating composites (Refs. 15,16). Formulation of CID-100, which contains MoS_2 and Sb_2O_3, was found to perform very well in oscillatory slider tests and high-speed journal tests. However, the performance was not as good in low-speed journal tests where the projected area load ranged from 1,500 to 6,000 psi (103×10^5 to 414×10^5 N/m^2) at a speed of 20 fpm (0.10 m/sec). The second formulation was CID-101, which contains graphite fibers as an additional ingredient. The CID-101 composites performed very well under all of the test conditions, exceeding the CID-100 performance notably in the high-load, low-speed journal tests. A review of this comparative performance has revealed the desirability of including more volume of chopped graphite fibers for evaluation especially at high loads. For this reason we have prepared additional CID-101 specimens for evaluation in oscillatory journal bearing tests; some of the specimens contain 18% and some 31% (vol.) graphite fibers. We have also included PTFE and ZnO powders as additives and polyphenylene sulfide (PPS) resin as a matrix.

A number of procedures and techniques have been incorporated into the standard method for preparation of the self-lubricating composites on this program. Some of those features are briefly set forth here for the record.

The various component materials are immersed in liquid dispersant and mixed for several minutes in a small commercial blender. The slurry is then transferred to a shallow container and the liquid dispersant is vaporized. The dried, caked residue is repowdered by hand-mixing with a spatula. The powder mixture is then transferred to a die for compression molding.

The compression molding is achieved by a combination of pressure and temperature. The powder is first compressed to the desired pressure. The die is then heated at approximately 5.4°F/min (0.05°K/s) to 400°F (478°K) and maintained at that temperature for 1 hr (3,600 s). The pressure is maintained until the die reaches room temperature. The pressure is then released and the specimen is pressed out of the die and is ready for carbonization.

Carbonization of the test specimens is conducted in a nonoxidizing gas environment, such as nitrogen or argon. The carbonization process is essentially a decomposition of the resin. Therefore, the degree of carbonization (or decomposition) is dependent on the temperature and time at temperature. However, the structure of the residue is dependent on the heating rate. If the specimens are heated too fast, the internal gas pressure (from both trapped and decomposed sources) is postulated to reach high enough levels to form cracks as pathways of escape. In our experience, the size and quantity of cracks formed in specific sized specimens has decreased with each reduction in heating rate. It has been reported that micro-pores are formed in the preparation of hard, crack-free specimens of vitreous carbon (Ref. 17) and serve as escape routes for decomposition gases. We have found that a heating rate of 0.1°C/min (0.0017°K/s) or less has been suitable in forming satisfactory specimens of the size discussed in this report.

Test specimens of various types can be easily prepared from the carbonized materials through the use of careful machining procedures. These materials are somewhat brittle in character. For this reason, small cuts and low-speed feeding are beneficial in lathe and milling operations. Some specimens have been regularly prepared with hacksaw forming, emery cloth smoothing, and grind finishing operations.

B. Formulation of Composites

A wide variety of materials, reported earlier (Refs. 15,16) to be compatible within the carbonized phenolic resin matrix includes self-lubricating solids (MoS_2, graphite, etc.), synergistic additives (Sb_2O_3, ZnO, etc.), and reinforcing fibers (carbon/graphite, glass, etc.). This wide range of compatibility offers great potential in composite formulation. Furthermore, in theory, the carbonization temperatures can be coordinated with specific formulations to satisfy particular applications.

Two formulations were selected from earlier work which appeared to offer great potential for application in solving current Air Force needs. These were designated CID-100 and CID-101. The CID-100 formulation contains $MoS_2 + Sb_2O_3$ in a carbonized phenolic resin (CPR) matrix. The CID-101 formulation contains graphite fibers in addition to the ingredients in CID-100. Specimens had been prepared with fiber content of 7, 13, 18, and 23% (vol.). Evaluation tests had been conducted primarily with the CID-100 specimens and CID-101 specimens which contained 18% graphite fibers. Little difference was reported in terms of friction and wear under light-load tests; however, under heavy loads (1,500 to 6,000 psi; 10.3 to 41.4 MN/m^2) the fibrous specimens exhibited much lower wear than the nonfibrous specimens.

Based on those results, and the contractual commitment to high-load bearings, we have extended our efforts in this program to investigating specimens with high fiber content.

Specimens have been prepared with 18, 31, 37, 44 and 59% (vol.) graphite fibers. A summary of these specimens and the relevant preparation parameters are given in Table I. Three different dies have been used in compression molding of these specimens. All sizes are suitable for preparing specimens for friction and wear screening. However, the small die (1.25 in diameter; 0.032 m diameter) is suitable for preparing only a single journal specimen; the journal liner can be pressed in the metal sleeve during compression molding (see Figure 1) or it can be machined and pressed into the metal sleeve. Two journal bearing liners (see Figure 2) can be machined from the medium-sized die specimens (1.75 in. diameter; 0.044 m diameter) shown in Figure 3, but only one liner can be pressed in place during the molding operation. The large die (2.0 in. diameter; 0.051 m diameter) has been employed to improve efficiency by speeding up the preparation of journal liners; three can be molded in place (see Figure 4) or three can be machined and press-fit into the metal sleeves. Lower pressures have been used in molding the larger specimens because of press limitations. However, initial screening results indicated no significant change in performance with the lower molding pressure. Therefore, numerous specimens were prepared in the large die, as shown in Table I; some molded directly into metal sleeves (Figure 5) and some molded as blanks for machining and press-fitting of test journals.

All of the carbonized specimens shown in Table I were carbonized in a nitrogen atmosphere at a heating rate no greater than 0.1°C/min (0.0017°K/s). Three final carbonization temperatures were used: 320, 400, and 550°C (593, 673, and 823°K).

The weight loss associated with carbonization of some of these specimens is shown in Table II. The percentage weight loss of the CID-101 composites carbonized at 400°C (673°K) averaged 5.53 and is within the range of data reported previously. The single CID-103 specimen exhibited a weight loss of 6.76%, which as expected, is within the scatter of data previously reported for CID-101 composites (Ref. 16).

The two CID-101 specimens which were carbonized at 550°C (823°K) exhibited an average weight loss of 11.4%. This weight change corresponds to approximately 60% loss of the resin if all of the loss is due to decomposition of the phenolic resin. The one CID-661 specimen lost 6.16% of its weight after being carbonized at 550°C (823°K), which corresponds to approximately the loss of 30% of the polyphenyline sulfide resin. That loss is very nearly the average weight loss of the phenolic samples carbonized at 400°C.

TABLE I

SUMMARY OF PREPARATION PARAMETERS FOR CPR SAMPLES

Specimen Number[a]	Graphite Fiber Content[b] (vol %)	Other Additives	Polymerization[c] Pressure (psi)	Polymerization[c] Pressure (MN/m^2)	Polymerization[c] Heating Rate (°C/min)	Polymerization[c] Heating Rate (°K/s)	Carbonization Maximum Temperature (°C)	Carbonization Maximum Temperature (°K)
Specimen size: 1.25 in. diameter (0.032 m)								
101-69[d]	18.6	Sb_2O_3	8,800	61	3.3	0.055	400	673
101-70[d]	18.6	Sb_2O_3	8,800	61	2.3	0.038	400	673
101-71[d]	18.6	Sb_2O_3	8,800	61	2.5	0.042	400	673
101-L-2	31.3	Sb_2O_3	16,400	113	2.3	0.038	315	588
101-L-3	31.3	Sb_2O_3	16,400	113	2.0	0.033	315	588
Specimen size: 1.75 in. diameter (0.044 m)								
101-68	18.6	Sb_2O_3	8,200	57	3.1	0.052	-	-
101-72	31.3	Sb_2O_3	8,200	57	2.9	0.048	400	673
101-74	31.3	Sb_2O_3	8,200	57	3.0	0.050	550	823
101-75	18.6	Sb_2O_3	8,200	57	3.2	0.053	550	823
101-76	18.6	Sb_2O_3	8,200	57	3.0	0.050	400	673
101-77	18.6	Sb_2O_3	8,200	57	2.8	0.047	400	673
101-78	31.3	Sb_2O_3	8,200	57	2.8	0.047	320	593
101-79	18.6	Sb_2O_3	8,200	57	2.9	0.048	-	-
101-80	18.6	Sb_2O_3	8,200	57	1.8	0.030	-	-
101-81	31.3	Sb_2O_3	8,200	57	2.6	0.043	400	673
103-2	18.6	ZnO	8,200	57	2.9	0.048	400	673
111-1	28.9	Sb_2O_3,PTFE	8,200	57	2.9	0.049	320	593
111-2	30.1	Sb_2O_3,PTFE	8,200	57	2.8	0.047	320	593
111-3	30.7	Sb_2O_3,PTFE	8,200	57	2.8	0.047	320	593
111-3a	30.7	Sb_2O_3,PTFE	8,200	57	2.8	0.047	400	673
121-1	18.6	Gr,BCM[h]	8,200	57	2.6	0.043	400	673
201-1	44.4	Sb_2O_3	8,200	57	3.0	0.050	400	673
SP-1	59.1	None	8,200	57	2.4	0.040	400	673
SPI-1	59.1	None	8,200	57	4.2	0.070	-	-
Specimen size: 2.00 in. diameter (0.051 m)								
101-82[d]	31.3	Sb_2O_3	6,300	43	3.7	0.062	400	673
101-83	31.3	Sb_2O_3	6,300	43	3.1	0.052	-	-
101-84	31.3	Sb_2O_3	6,300	43	2.8	0.047	-	-
101-85	31.3	Sb_2O_3	6,300	43	3.2	0.053	-	-
101-86	37.8	Sb_2O_3	6,300	43	2.4	0.040	400	673
101-87[d]	31.3	Sb_2O_3	6,300	43	2.9	0.048	400	673

TABLE I (Concluded)

Specimen Number[a]	Graphite Fiber Content[b] (vol %)	Other Additives	Polymerization[c] Pressure (psi)	Pressure (MN/m^2)	Heating Rate (°C/min)	Heating Rate (°K/s)	Carbonization Maximum Temperature (°C)	(°K)
101-88[d]	31.3	Sb_2O_3	6,300	43	2.4	0.040	400	673
101-89[d]	37.8	Sb_2O_3	6,300	43	2.0	0.033	400	673
101-90	31.3	Sb_2O_3	6,300	43	3.6	0.060	-	-
101-91[e]	31.3	Sb_2O_3	6,300	43	2.7	0.043	400	673
111-4	30.7	Sb_2O_3,PTFE	6,300	43	2.3	0.038	-	-
111-5	30.7	Sb_2O_3,PTFE	6,300	43	2.4	0.040	-	-
111-6[e]	30.7	Sb_2O_3,PTFE	6,300	43	2.7	0.045	400	673
111-7[f]	30.7	Sb_2O_3,PTFE	9,900	68	1.9	0.031	400	673
103-3	31.3	ZnO	6,300	43	2.9	0.048	400	673
103-4	31.3	ZnO	6,300	43	2.9	0.048	-	-
103-5[d]	31.3	ZnO	6,300	43	2.5	0.042	400	673
103-6[d]	31.3	ZnO	6,300	43	2.8	0.047	400	673
661-1	31.4	ZnO	6,300	43	~ 7.5	0.125	550	823
101-L-1	31.3	Sb_2O_3	6,300	43	3.2	0.053	315	588
1101-1	31.3[g]	Sb_2O_3	6,300	43	2.9	0.048	-	-
1101-2	31.3[g]	Sb_2O_3	6,300	43	2.8	0.047	315	588
1101-3	31.3[g]	Sb_2O_3	6,300	43	3.0	0.050	370	643
1101-4	31.3[g]	Sb_2O_3	6,300	43	3.1	0.052	427	700
1101-5[e]	31.3[g]	Sb_2O_3	6,300	43	2.4	0.040	400	673

a/ All compositions were mixed in a commercial blender for at least 5 min; Freon TF solvent was used as the dispersant. All mixtures were dried overnight prior to hot-pressing. Compositions numbered 101-, 103-, 111-, 121-, 201-, 1101-, and SP- utilize a phenolic resin matrix; those numbered 661- utilize a polyphenylene sulfide resin matrix; those labeled SPI- utilize a polyimide resin matrix.

b/ These graphite fibers are identified as T50 in our data books. The supplier lists the tensile strength at 250,000 psi (1.7×10^9 N/m^2), Young's modulus at 50×10^6 psi (345×10^9 N/m^2), and the specific gravity as 1.7.

c/ All 101-, 103-, 111-, 121-, 201-, and SP- specimens were heated to 400°F (478°K) at the indicated pressure and heating rate and held for 2 hr (7,200s); some of the 1101- specimens were heated to higher temperatures while under pressure in the die; the 661-1 specimen was heated to 750°F (672°K) and held for 10 min (600s); the SPI-1 specimen was heated to 660°F (622°K) and held for 30 min (1,800s); all specimens were allowed to cool to room temperature while under pressure.

d/ These specimens were molded directly into 5/8 in. bore self-aligning journal sleeves; one sleeve in each small specimen and three in each large specimen.

e/ These specimens were molded directly into two steel cylindrical sleeves and two steel self-aligning journal sleeves.

f/ This specimen was molded directly into a spherical bearing to form both the journal liner and spherical seat.

g/ Glass fiber was substituted for graphite fiber in these composites.

h/ BCM is a powder prepared from a fused mixture of BaF_2, CaF_2, and MgF_2.

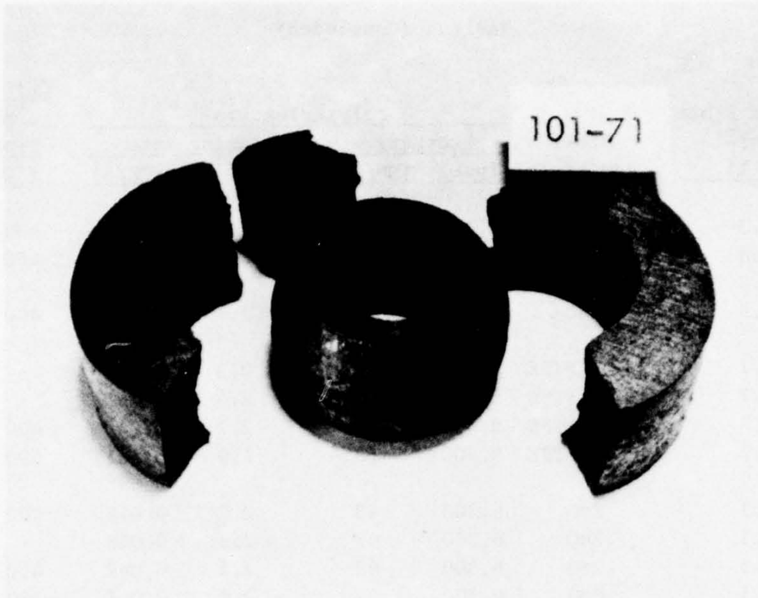

Figure 1 - Photograph of Journal Specimen CID-101-71, Molded and Carbonized in Place

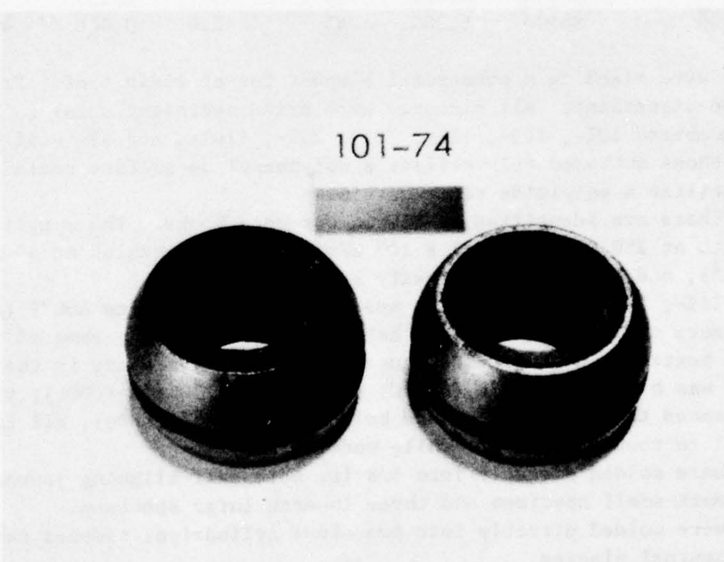

Figure 2 - Photograph of Journal Specimens, CID-101-74, Machined After Carbonization and Pressed in Place as Journal Liners

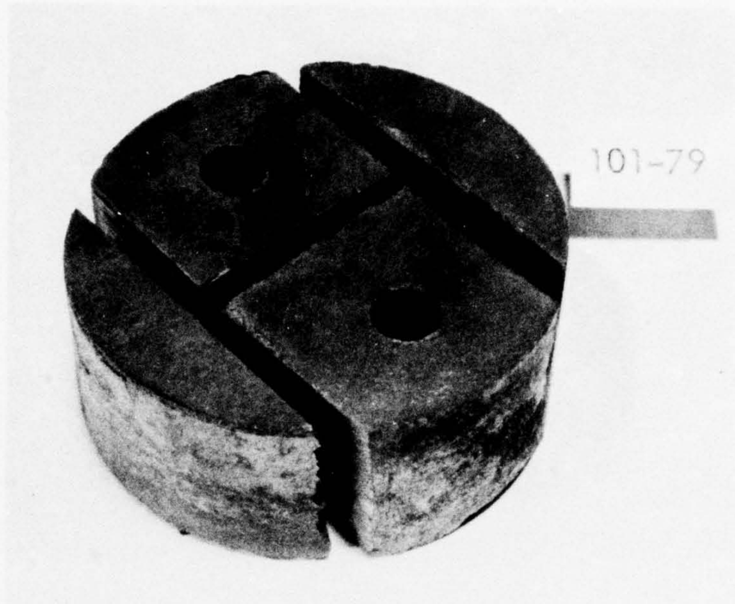

Figure 3 - Photograph of Composite Slug, CID-101-79, Sectioned Before Carbonization

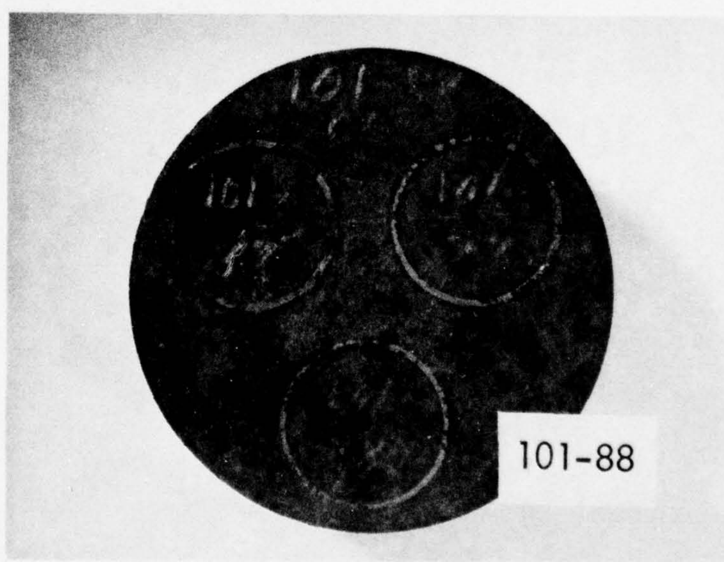

Figure 4 - Photograph of Composite CID-101-88, Compression Molded Into Three Metal Journal Sleeves

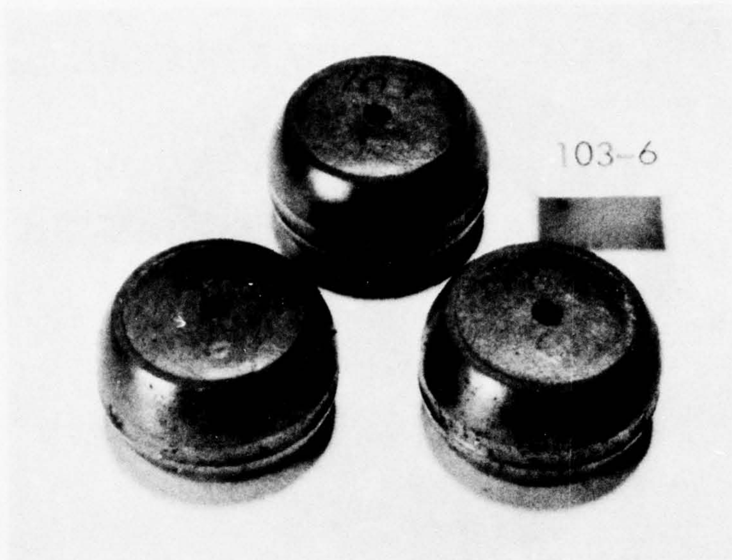

Figure 5 - Photograph of Composite CID-103-6, Molded and Carbonized Directly in Three Metal Journal Sleeves and Ready for Machining to Specified Bore Size

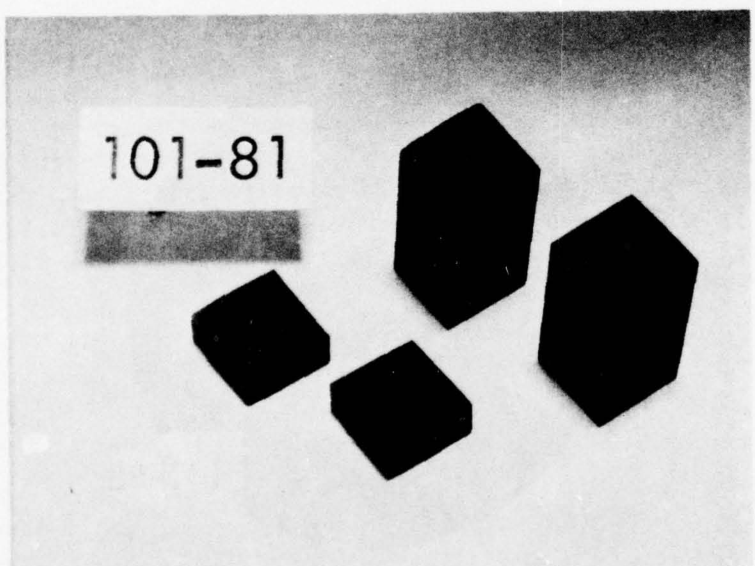

Figure 6 - Photograph of Compression Test Specimens Fabricated From Composite CID-101-81

TABLE II

WEIGHT LOSS OF SEVERAL COMPOSITES DURING CARBONIZATION

Specimen[a/]	Contents	Carbonization Temperature °C	°K	Weight Loss (%)
101-76 (3x)	Composite only	400	673	4.95
101-77 (3x)	Composite only	400	673	5.87
101-81 (6x)	Composite only	400	673	5.78
101-82 (6x)	Composite plus 3 steel journals	400	673	4.22
103-6 (6x)	Composite only	400	673	6.76
101-75 (3x)	Composite only	550	823	11.74
101-74 (6x)	Composite only	550	823	11.06
661-1 (6x)	Composite only	550	823	6.16

a/ The 101- specimens consist of MoS_2, Sb_2O_3, and graphite fibers in a phenolic matrix; the 661- specimens consist of MoS_2, ZnO, and graphite fibers in a polyphenylene sulfide resin; the 103- specimens consist of MoS_2, ZnO, and graphite fibers in a phenolic matrix. The 3x designation corresponds to 18.6% (vol.) of graphite fibers and 6x corresponds to 31.3% (vol.) graphite fibers.

C. Compressive Strength Data for Self-Lubricating Composites

Compression tests have been conducted on numerous self-lubricating composite specimens to determine the compressive strength of the materials. The test procedure used was similar to that described in ASTM Method D-695-63T. The crosshead speed in all tests was 0.10 cm/min (17 μm/s; 0.039 in/min). Stress-strain curves were plotted during each test and all curves were smooth and orderly up to a yield or fracture point.

The specimens were prepared following a set procedure. Rough-cut slabs were ground to size in a series of lapping dies until the cross-sectional dimensions were achieved. In a similar fashion, end faces were lapped flat and parallel to the chosen length. The cross section of all specimens was 1/4 x 1/4 in. (0.006 m); the tall specimens were 1/2 in. (0.013 m) long and the short specimens were 1/8 in (0.003 m) long. A photograph of typical compression test specimens is shown in Figure 6.

The data from all the compression tests have been reduced and are summarized in Table III. The compressive strength, compressive yield strength, and elastic modulus have been calculated for each specimen as shown in Table III. The values are arranged in three groups: carbonized, uncarbonized, and a special series of specimens. The first portion of Table III shows values calculated for carbonized specimens arranged according to composition and, within each composition, in order of increasing fiber content. The second portion of Table III shows values calculated for uncarbonized specimens arranged in similar order. In some cases we have been able to prepare compression test specimens from both carbonized and uncarbonized portions of the same composite. The last portion of Table III shows values calculated for composites which were prepared with glass reinforcing fibers, substituted on a volume basis for grahite fibers used in the other composites. The first of these composites was uncarbonized, while the remaining three were carbonized under pressure in the die to maximum temperatures of 600, 700, and 800°F (315, 370, and 427°C; 588, 643, and 700°K), respectively.

Analysis of the data in Table III indicate several trends. First of all, higher compressive strength is generally shown for short specimens than for tall specimens. Since the journal bearing liners are usually thinner than these short specimens, it seems reasonable to expect that even higher static loads might be supported. Of course, nonuniform load distribution and dynamic stresses would limit the useful load capacity in application. Secondly, there appears to be little difference in compressive strengths of CID-101 composites which contain either 18% (3x) or 31% (6x) graphite fibers (see Figure 7). If anything, the specimens with 18% appear to be slightly stronger. The third observation is that the uncarbonized specimens are generally stronger than the carbonized specimens (see Figures 7, 8, and 9).

TABLE III

A SUMMARY OF COMPRESSION TEST DATA FOR NUMEROUS SELF-LUBRICATING COMPOSITES

Composite Number[a]	Fiber (%)[b]	Size[c]	Compressive Strength (10^3 lb/in^2)	Compressive Strength (MN/m^2)	Compressive Yield Strength (10^3 lb/in^2)	Compressive Yield Strength (MN/m^2)	Elastic Modulus (10^6 lb/in^2)	Elastic Modulus (GN/m^2)
Carbonized Specimens[d]								
100-61R	0	S	8.57	59.1	8.57	59.1	0.151	1.04
		T	8.96	61.8	8.74	60.2	0.036	2.32
100-63	0	S	17.1	118.0	16.4	113.0	0.216	1.49
		T	9.32	64.2	8.43	58.1	0.487	3.36
101-4	7	S	13.4	92.1	11.6	79.8	0.112	0.77
		T	7.54	52.0	1.55	10.7	0.252	1.74
101-5	7	S	13.2	91.2	10.8	74.2	0.164	1.13
		T	19.4	134.0	13.4	92.4	0.594	4.10
101-11	7	S	15.9	110.0	15.5	107.0	0.309	1.44
		T	6.24	43.0	5.35	36.9	0.341	2.35
101-76	18	S	16.9	116.0	14.6	101.0	0.233	1.61
		S	12.4	85.4	11.6	79.9	0.164	1.13
		T	15.4	106.0	12.9	89.0	0.686	4.73
		T	9.76	67.2	9.17	63.2	0.497	3.43
101-75	18	S	21.4	148.0	21.4	148.0	0.257	1.77
		T	10.3	70.7	9.14	63.0	0.687	4.74
101-33	23	S	11.7	80.8	9.29	64.0	0.200	1.38
		T	7.18	49.5	6.96	48.0	0.525	3.62
101-29	23	S	12.1	83.4	11.6	80.3	0.199	1.37
		T	9.16	63.1	9.16	63.1	0.568	3.92
101-78	31	S	21.1	146.0	18.9	130.0	0.248	1.71
		S	13.9	95.8	12.4	85.4	0.161	1.11
		T	15.0	103.0	8.49	58.5	0.726	5.01
		T	6.11	42.1	5.64	38.9	0.396	2.73
101-74	31	S	15.2	105.0	15.2	105.0	0.248	1.71
		S	16.2	111.0	13.3	91.7	0.249	1.72
		S	9.31	64.1	7.49	51.6	0.168	1.16
101-86	38	S	13.6	93.9	11.6	80.1	0.239	1.65
		S	7.55	52.0	6.21	42.8	0.148	1.00
		T	12.5	86.1	11.6	80.0	0.834	5.75
		T	5.89	40.6	5.44	37.5	0.484	3.34
102-1	0	S	12.6	87.0	12.4	85.4	0.207	1.43
		T	9.25	63.8	5.41	37.3	0.560	3.86
103-2	18	S	9.58	66.0	8.64	59.6	0.123	0.85
		S	8.44	8.2	2.67	18.4	0.146	1.01
103-5	31	S	13.1	90.0	12.6	86.9	0.144	0.99
		T	8.29	57.2	5.38	37.1	0.425	2.93

TABLE III (Continued)

Composite Number[a]	Fiber (%)[b]	Size[c]	Compressive Strength		Compressive Yield Strength		Elastic Modulus	
			(10^3 lb/in^2)	(MN/m^2)	(10^3 lb/in^2)	(MN/m^2)	(10^6 lb/in^2)	(GN/m^2)
201-1	44	S	6.49	44.7	5.82	40.1	0.138	0.95
		T	13.0	89.3	9.38	64.7	0.745	5.14
SP-1	59	S	10.4	71.4	9.23	63.6	0.088	0.61
		S	6.67	46.0	6.34	43.7	0.130	0.898
		T	5.17	35.6	5.17	35.6	0.291	2.01
		T	3.84	26.5	2.59	17.8	0.283	1.95
111-1	29	S	15.4	106.0	13.4	92.4	0.199	1.37
		S	18.1	125.0	17.8	123.0	0.223	1.54
111-2	30	S	33.8	233.0	31.6	218.0	0.406	2.80
		T	23.6	163.0	21.8	150.0	1.04	7.14
111-3	31	S	27.4	189.0	24.9	172.0	0.297	2.05
		[illegible]	30.7	212.0	30.7	212.0	0.321	2.21
		[illegible]	17.9	123.0	16.7	115.0	0.189	1.30
Uncarbonized Specimens[e]								
100-60	0	S	25.7	177.0	24.4	168.0	0.248	1.71
		T	8.38	57.8	7.94	54.7	0.400	2.76
100-61R	0	S	11.7	80.9	11.3	77.8	0.180	1.24
		S	4.50	31.0	3.38	23.3	0.083	0.57
101-5	7	S	17.1	118.0	16.4	113.0	0.197	1.36
		T	17.8	123.0	8.89	61.3	0.613	4.23
101-11	7	S	20.3	140.0	13.4	92.4	0.167	1.15
		T	11.6	79.7	9.78	67.4	0.594	4.10
101-76	18	S	32.9	227.0	30.9	213.0	0.270	1.86
		S	19.6	135.0	17.6	121.0	0.189	1.30
		T	24.0	166.0	19.6	135.0	0.793	5.47
		T	14.8	102.0	12.4	85.4	0.605	4.17
101-L-3	31	S	16.9	117.0	11.7	81.0	0.144	0.99
		T	15.5	107.0	13.5	92.8	0.660	4.55
101-74	31	S	30.0	207.0	28.2	195.0	0.264	1.82
		S	14.6	101.0	14.6	101.0	0.187	1.29
		T	18.9	130.0	17.4	120.0	0.876	6.04
		T	14.7	101.0	13.5	93.0	0.635	4.38
101-81	31	S	19.3	133.0	18.6	129.0	0.178	1.23
		T	20.9	144.0	17.8	123.0	0.721	4.97
103-5	31	S	29.8	206.0	28.5	196.0	0.252	1.74
		T	20.4	141.0	19.3	133.0	0.715	4.93
SP-1	59	S	37.3	257.0	33.1	228.0	0.258	1.78
		S	19.9	137.0	19.9	137.0	0.143	0.985
		T	29.4	202.0	20.2	139.0	0.854	5.89
		T	19.1	132.0	13.6	93.7	0.605	4.17

TABLE III (Concluded)

Composite Number[a]	Fiber (%)[b]	Size[c]	Compressive Strength (10^3 lb/in^2)	Compressive Strength (MN/m^2)	Compressive Yield Strength (10^3 lb/in^2)	Compressive Yield Strength (MN/m^2)	Elastic Modulus (10^6 lb/in^2)	Elastic Modulus (GN/m^2)
111-2	30	S	26.7	184.0	23.5	162.0	0.286	1.97
		T	26.7	184.0	26.7	184.0	1.10	7.60
111-3	31	S	24.8	171.0	22.4	154.0	0.293	2.02
		S	35.3	243.0	34.6	239.0	0.345	2.38
		S	18.6	128.0	17.0	117.0	0.183	1.26
WDC-130[f]	0	S	17.6	121.0	12.4	85.5	0.111	0.764
		S	16.7	115.0	12.3	84.8	0.106	0.730
WDC-140[f]	0	S	25.0	172.0	21.1	145.0	0.264	1.82
		T	20.7	143.0	9.68	66.7	0.677	4.67
Special Series Specimens[g]								
1101-1	31	S	36.3	250.0	24.0	166.0	0.267	1.84
		S	24.7	170.0	23.9	165.0	0.194	1.34
		T	14.7	101.0	12.9	88.8	0.551	3.80
		T	18.2	125.0	16.9	116.0	0.586	4.04
1101-2	31	S	28.0	193.0	25.3	174.0	0.244	1.68
		S	12.5	86.1	5.58	38.4	0.108	0.748
		T	16.3	112.0	13.1	90.3	0.679	4.68
		T	13.9	95.8	12.9	88.9	0.466	3.21
1101-3	31	S	27.5	190.0	25.5	176.0	0.264	1.82
		T	18.2	126.0	12.5	86.4	0.757	5.22
1101-4	31	S	24.7	170.0	23.1	159.0	0.245	1.69
		T	18.1	125.0	12.6	87.2	0.725	5.00

Note: The crosshead speed in all tests was 0.039 in/min (0.10 cm/min; 17 μm/s).

a/ The composition of these composites, as prepared, is as follows:

- CID-SP: graphite fibers in a phenolic resin matrix.
- CID-100: MoS_2 + Sb_2O_3 in a phenolic resin matrix.
- CID-101, 201: MoS_2 + Sb_2O_3 + graphite fibers in a phenolic resin matrix.
- CID-102: MoS_2 + ZnO in a phenolic resin matrix.
- CID-103: MoS_2 + ZnO + graphite fibers in a phenolic resin matrix.
- CID-111: MoS_2 + Sb_2O_3 + teflon powder in a phenolic resin matrix.
- CID-1101: MoS_2 + Sb_2O_3 + glass fibers in a phenolic resin matrix.
- WDC-130, 140: MoS_2 + Sb_2O_3 in a polyphenelyene sulfide resin matrix.

b/ Fiber content is expressed in volume percent based on initial ingredients; the glass fibers (CID-1101) and long graphite fibers (CID-101-L) were approximately 1/4 to 3/4 in (0.006 to 0.013 m) long; the graphite fibers in all other specimens were chopped to 1/8 in. (0.003 m) lengths.

c/ The short (S) specimens were 1/8 in. (0.003 m) high. The tall (T) specimens were 1/2 in. (0.013 m) high.

d/ These specimens were carbonized slowly to a maximum temperature of 752°F (400°C; 673°K).

e/ The uncarbonized specimens were subjected to a 2-hr (7,200 s) dwell at 400°F (204°C; 477°K) while under pressure in a die.

f/ WDC-130 and WDC-140 specimens were supplied by the Phillips Petroleum Co.; they were extrusion molded at approximately 525°F (275°C; 548°K).

g/ Specimen CID-1101-1 was not carbonized; specimens CID-1101-2, -3, and -4 were carbonized under pressure in the forming die at 600, 700, and 800°F (315, 370, and 427°C; 588, 643, and 700°K), respectively.

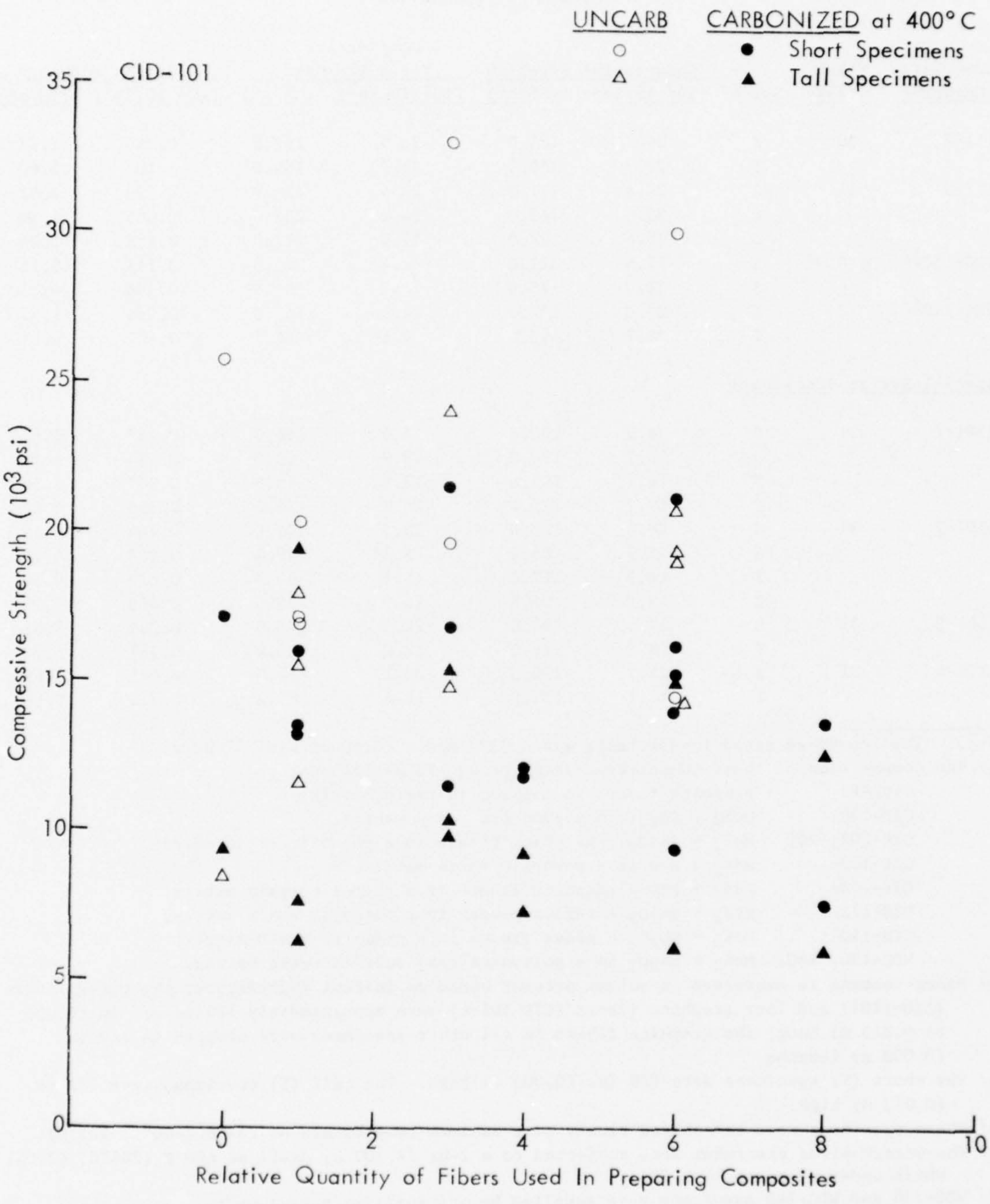

Figure 7 - Plot of Compressive Strength Versus Fiber Content of CID-101 Composites

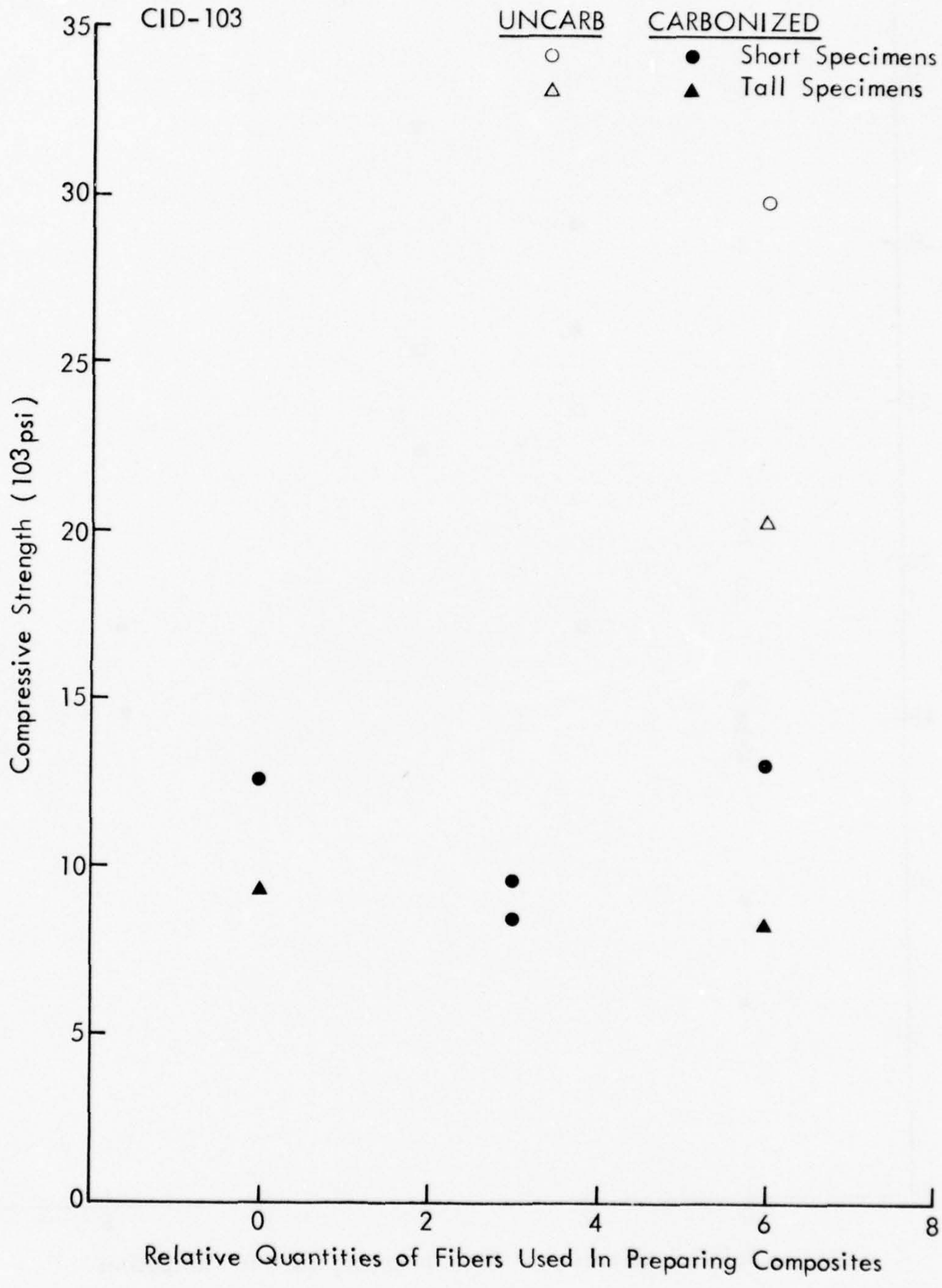

Figure 8 - Plot of Compressive Strength Versus Fiber Content of CID-103 Composites

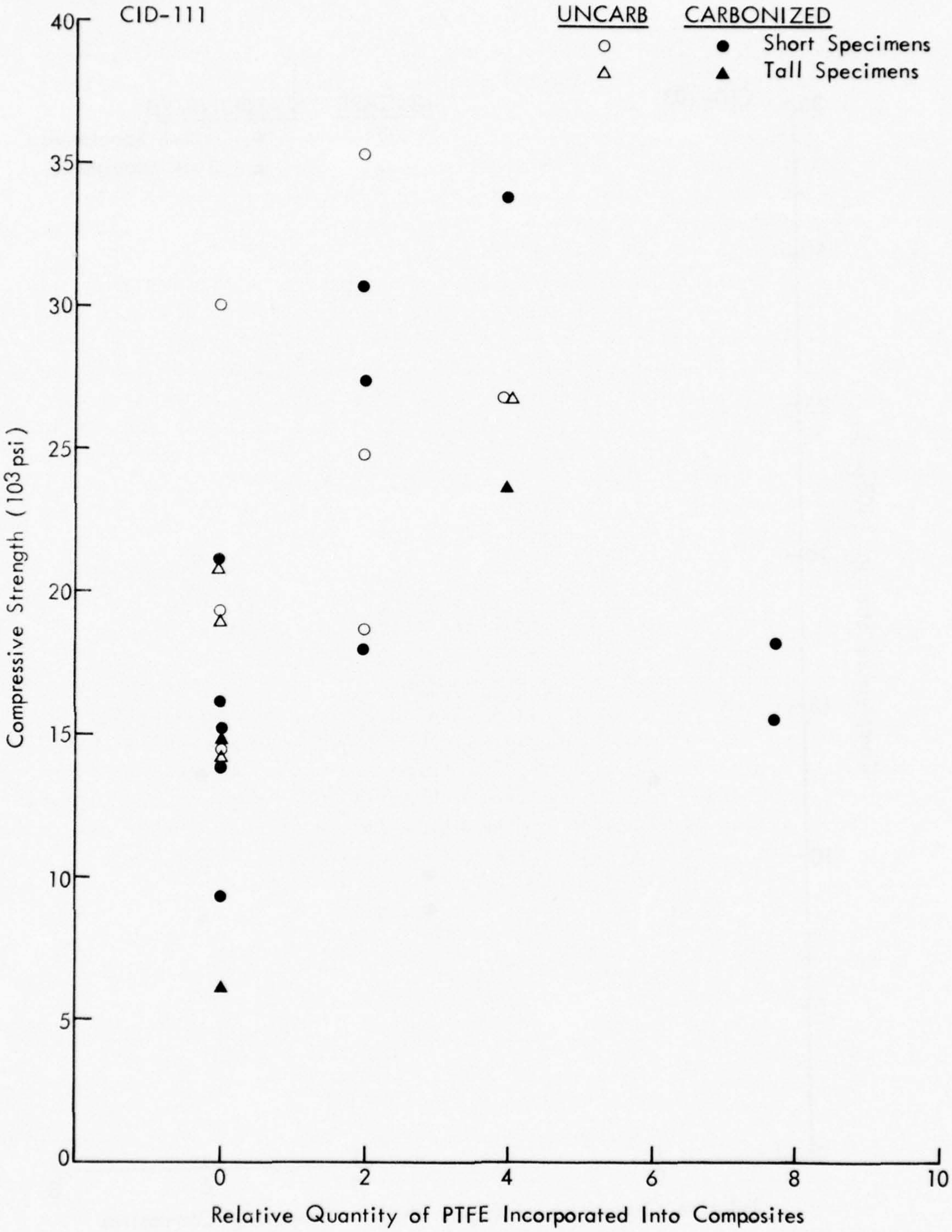

Figure 9 - Plot of Compressive Strength Versus PTFE Content for CID-111 Composites. Values for CID-101 are used to indicate the zero level of PTFE.

The strongest CID-101 individual specimen (32,900 psi; 227 MN/m^2) was uncarbonized and contained 18% graphite fibers. The strongest carbonized CID-101 individual specimen (21,400 psi; 148 MN/m^2) also contained 18% fibers. The fourth observation is that CID-111-3 specimens, which contain 2% PTFE, appear to be the strongest of all these composites which contain both MoS_2 + Sb_2O_3 pigment and graphite fiber. The maximum compressive strength for CID-111, uncarbonized is 35,300 psi (243 MN/m^2) and for the carbonized specimens is 33,800 psi (212 MN/m^2). The fifth observation is that specimens prepared much earlier on the program with a different phenolic resin appear to be weaker than the newer specimens prepared with the current type of phenolic resin. All of the CID-101 specimens shown in Table III (and Figure 7) which contain 7 and 23% (1x and 4x) fibers were prepared with the older resin and some of the mixing procedures may have been slightly different. The sixth observation is that there appears to be little effect on the compressive strength of CPR composites prepared with glass fibers, where various degrees of carbonization were achieved while under pressure in the forming die (see Figure 10). The seventh observation is that the composites with the highest fiber content, SP-1 (59%) and CID-201 (44%) do not exhibit the highest compressive strength especially in the carbonized condition (compare Figures 7 and 11). All of these observations were based on the data summarized in Table III.

Some compressive strength data has been screened from various sources for comparison of CPR properties with other self-lubricating materials. The comparative data, summarized in Table IV, shows that generally only the metal matrix composites, such as Molalloy 103, 104, and 108 exhibit consistently higher compressive strength than the CPR composites. Although the property values of Molalloy compositions are excellent in many respects, the high cost and high specific gravity does limit their application in many areas.

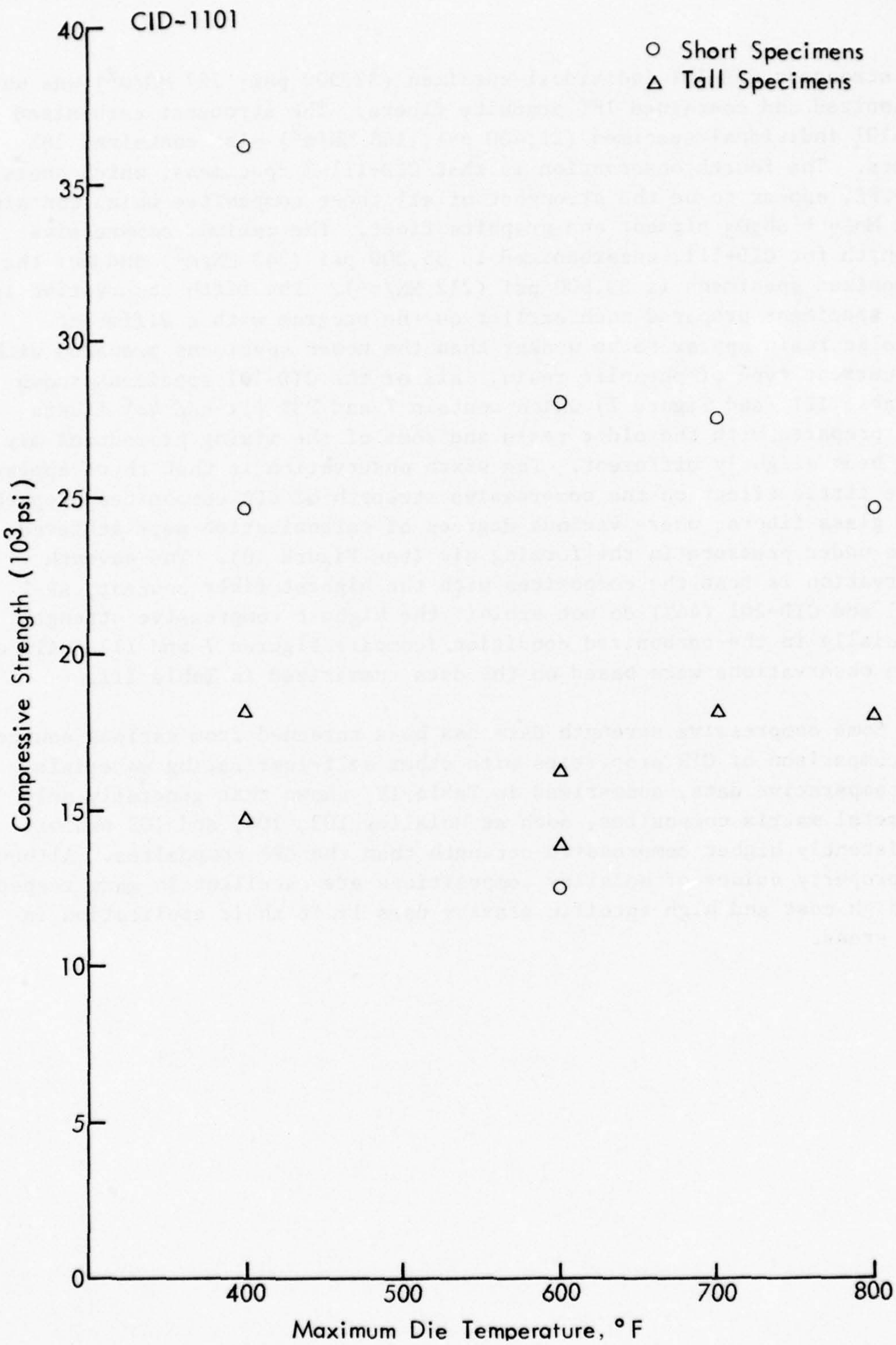

Figure 10 - Plot of Compressive Strength Versus Maximum Die Temperature for CID-1101 Composites

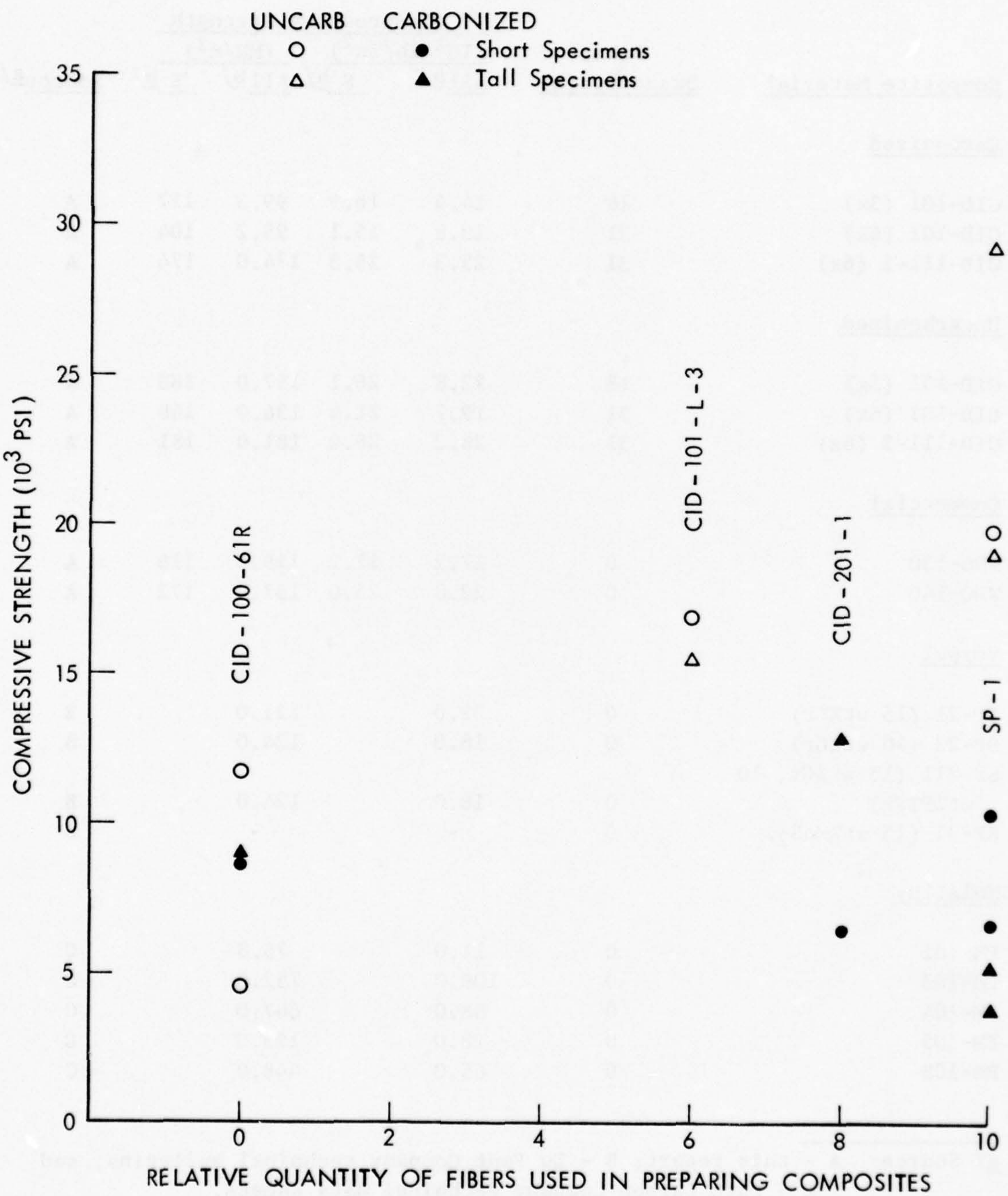

Figure 11 - Plot of Compressive Strength Versus Fiber Content for Exploratory Composites

TABLE IV

COMPRESSIVE STRENGTH DATA FOR EXPERIMENTAL AND COMMERCIAL SELF-LUBRICATING COMPOSITES

Composite Material	Fiber Quantity (%)	Compressive Strength (10^3 lb/in^2) All[b]	S[b]	Compressive Strength (MN/m^2) All[b]	S[b]	Source[a]
Carbonized						
CID-101 (3x)	18	14.4	16.9	99.3	117	A
CID-101 (6x)	31	13.8	15.1	95.2	104	A
CID-111-3 (6x)	31	25.3	25.3	174.0	174	A
Uncarbonized						
CID-101 (3x)	18	22.8	26.1	157.0	180	A
CID-101 (6x)	31	19.7	21.4	136.0	148	A
CID-111-3 (6x)	31	26.2	26.2	181.0	181	A
Commercial						
WDC-130	0	17.2	17.2	119.0	119	A
WDC-140	0	22.8	25.0	157.0	172	A
Vespel						
SP-21 (15 wt%Gr)	0	32.0		221.0		B
SP-22 (40 wt%Gr)	0	18.0		124.0		B
SP-211 (15 wt%Gr, 10 wt%PTFE)	0	18.0		124.0		B
SP-31 (15 wt%MoS_2)	0	-		-		B
Molalloy						
PM-101	0	11.0		75.8		C
PM-103	0	109.0		752.0		C
PM-104	0	88.0		607.0		C
PM-105	0	28.0		193.0		C
PM-108	0	65.0		448.0		C

a/ Source: A - this report; B - Du Pont Company technical bulletins; and C - Pure Carbon Company technical data sheets.

b/ All, refers to an average of results from both short and tall specimens; S, refers to an average of values from only the short specimens.

III.

TRIBOLOGICAL EVALUATION OF SELF-LUBRICATING COMPOSITES

The tribological properties (friction, wear, and lubrication) of the self-lubricating composites developed on this program have been determined under a variety of test conditions. Two types of test devices have been used with loads ranging from 1,500 to 27,450 psi (10.3 to 189.3 MN/m^2), speeds from 0.25 to 36 fpm (0.0012 to 0.183 m/s), and temperatures from 100 to 600°F (311 to 588°K). These test devices and the specimen configurations are described briefly under separate headings, followed by a presentation of the corresponding data under compositional headings.

A. Test Equipment

Screening data have been obtained in oscillatory sliding tests with flat specimens in full contact with a flat steel plate. The final evaluation data have been obtained on oscillatory journal tests with cylindrical sleeve specimens in contact with cylindrical steel shafts.

1. The oscillatory slider test device is shown photographically in Figure 12. A schematic of the specimen configuration is shown in Figure 13. The composite specimen is cemented onto the wear block and ground flat to mate with the flat steel wear plate. The wear plate is attached to a holder which is mounted on a flat, linear roller bearing assembly and constrained to sliding along a line by needle bearings. An eccentrically mounted shaft drives the wear plate in flat, oscillatory motion. The length of stroke can be adjusted by the eccentric mounting position. Stroke lengths of 1.0 and 4.0 in. (0.025 and 0.10 m) have been used in these experiments. Loads as high as 1,500 lb (6,675 N) may be applied through a dead weight loading system. The load per unit test area is adjusted both by modifying the dead weight load and by the test specimen size. The specimen sizes (contact area) used in experiments on this program include 0.5 x 1.0 in. (0.0127 x 0.0254 m) 0.25 x 0.5 in. (0.0063 x 0.0127 m), 0.25 x 0.25 in. (0.0063 x 0.0063 m), and 0.25 in. diameter (0.0063 m).

2. The oscillatory journal test device is shown photographically in Figure 14. A schematic of the test configuration is shown in Figure 15. The composite specimen is either molded as a journal liner or machined and press-fit as a liner in the ball portion of a self-aligning bearing.

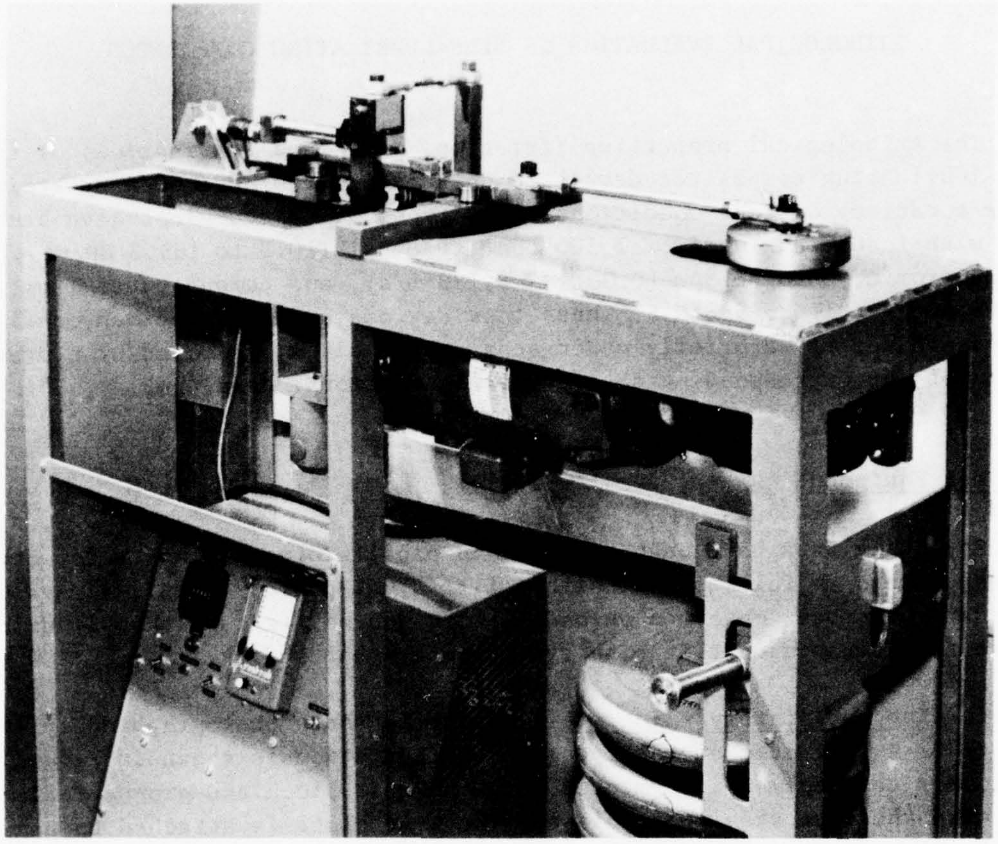

Figure 12 - Photograph of Oscillatory Slider Friction and Wear Machine

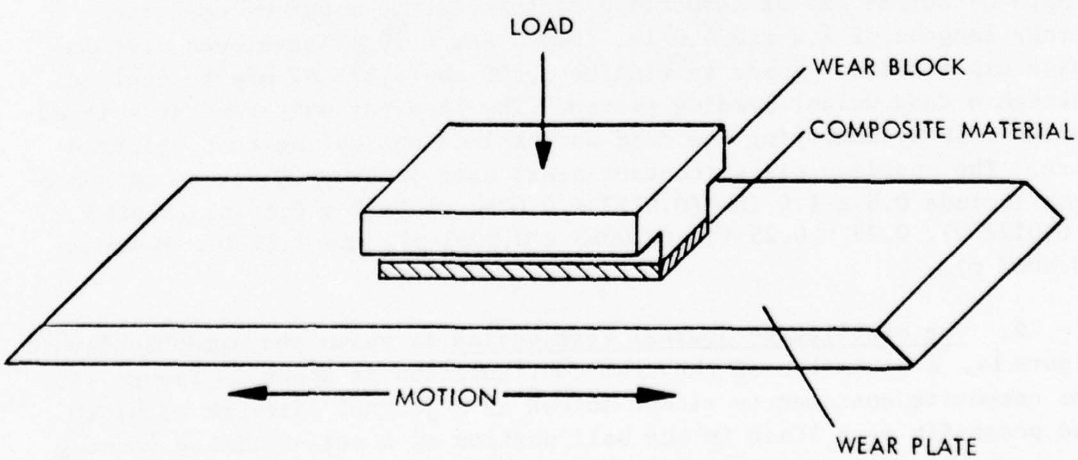

Figure 13 - Test Specimen Configuration for the Oscillatory Slider Friction and Wear Machine

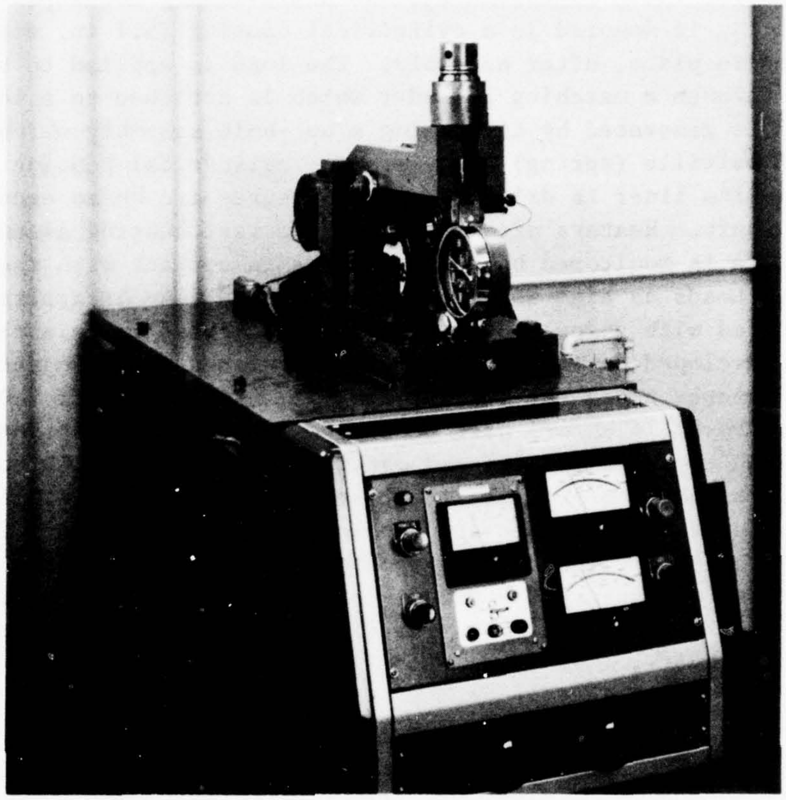

Figure 14 - Photograph of Oscillatory Journal Bearing Tester

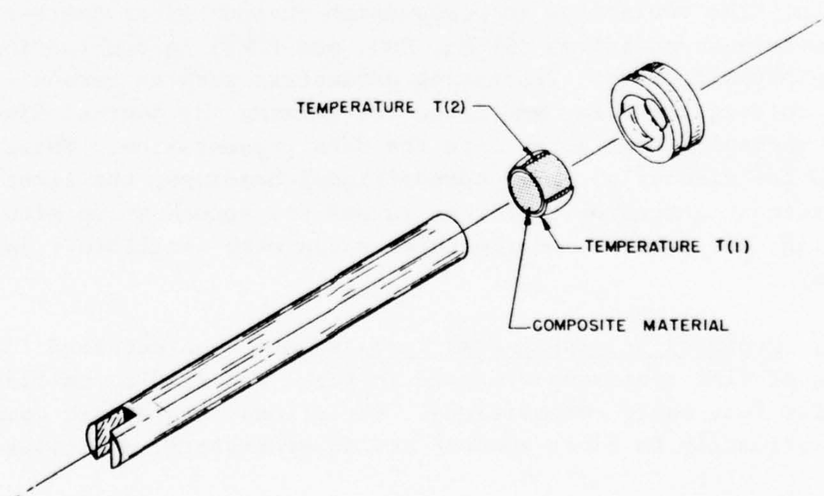

Figure 15 - Schematic of Test Configuration Used in Oscillatory Journal Tests

The composite liner is tested against a stationary dowel-pin shaft. The test bearing is mounted in a cylindrical housing (5.7 in. diameter; 0.145 m) and keyed in place, after assembly. The load is applied to the cylindrical housing through a matching cylinder which is attached to a loading arm. The load is generated by tightening a nut-bolt assembly which includes a stack of belville (spring) washers. The cylindrical housing which contains the composite liner is driven in a $\pm$ 15 degree arc by an eccentrically mounted shaft. Heaters are mounted in the test bearing assembly and the temperature is monitored by thermocouples in contact with the composite housing. Loads as high as 10,000 lb (44,500 N) may be applied; the load is monitored with a force gage. Unit loads listed in this report for composites developed on this program are calculated on a projected area basis (shaft diameter times the bearing length). Unit loads of 2,000 to 12,000 psi (13.8 to 82.74 MN/m^2) have been used in evaluating composites at temperatures up to 600°F (588°K) and oscillatory speeds of 100 cpm (1.67 cps) which corresponds to average linear speeds of 2.18 fpm (0.011 m/s). Similar tests have been planned at unit loads up to 40,000 psi (274 MN/m^2) at 11 cpm (0.184 cps). However, alignment and shaft deflection problems and limitations in compressive strength of the composites have limited the test program to loads of 8,000 psi (55.16 MN/m^2) at the low speed of 11 cps (0.184 cps).

B. Test Data for Self-Lubricating Composites

Self-lubricating composites of several compositions have been subject to friction and wear tests. Phenolic resin has been used as the matrix in all but one of the compositions, for which polyphenylene sulfide (PPS) resin was used. The variations in composition include fiber content (up to 59%) and synergistic additives (Sb_2O_3, ZnO, and PTFE) in combination with the primary pigment, MoS_2. Processing parameters such as carbonizing temperature, molding pressure, and method of forming the journal liners are additional variables that enter into the data presentation. These are all grouped for discussion under compositional headings; the first group deals with ordinary screening test results and the second group with special screening test results and the third group with oscillatory journal test results.

1. Ordinary screening test results have been obtained in oscillatory sliding of flat specimens cemented in place and sliding on flat mating surfaces for four basic compositions. Variations within each composition relate primarily to fiber content and to synergistic additives.

a. CID-101 composites consist of MoS_2 + Sb_2O_3 + graphite fibers in carbonized phenolic resin matrix. Data from CID-101 (3x) specimens containing 18.6% graphite fibers in flat, oscillatory sliding tests are shown

in Table V. Two of the test specimens were carbonized at 400°C (673°K) and one at 550°C (823°K). The wear factors remained consistently low at loads of 1,500 and 3,000 psi (10.3 and 20.7 MN/m^2). A noticeable increase in wear factor occurred at 6,000 psi (41.4 MN/m^2) and the specimens failed at double that unit load. A plot of wear factor versus load is shown in Figure 16.

CID-101 (6x) specimens containing 31.3% graphite fibers performed better than those with only 18.6% fibers. The data for these 6x specimens carbonized at either 400 or 550°C (673 or 823°K) are summarized in Table VI. The wear factors are very similar to those of the 3x samples at loads as high as 6,000 psi (41.4 MN/m^2). However, the 6x specimen that was carbonized at 400°C did complete both tests at 12,000 psi (82.7 MN/m^2) although the wear factor was very high in the low speed test. Failure occurred quickly when the load was increased to 16,800 psi (115.8 MN/m^2). These wear factors are plotted versus load in Figure 17. The specimen that was carbonized at 550°C failed quickly in the high-load, low-speed test. Comparative data for an uncarbonized specimen of CID-101 (6x) are shown in Table VII and Figure 17. That the uncarbonized specimen completed all the tests and exhibited reasonable wear rates indicates that at room temperature the fiber reinforcement may be more effective at some test levels than the carbonizing process. Photographs of some specimens used in the light-load tests are shown in Figure 18 and some used in the high-load tests are shown in Figure 19.

Screening tests were also conducted with CID-101 (8x) specimens which contain 37.8% graphite fibers. These data are summarized in Table VIII for specimens carbonized at 400°C and for specimens that were not carbonized. The carbonized specimens exhibited the lowest and most consistent wear rates of any carbonized CID-101 specimens at loads of 6,000 and 12,000 psi (41.4 and 82.7 MN/m^2). The uncarbonized specimen failed quickly at the high load. A plot of the wear factor versus load is shown in Figure 20 for these 8x specimens; a carbonized test specimen is shown in Figure 21.

b. CID-103 composites are prepared as mixtures of MoS_2, ZnO,* and graphite fibers in a phenolic resin matrix. Screening friction and wear tests have been conducted with carbonized specimens containing 18.6% graphite fibers and with uncarbonized specimens containing 31.3% fibers.

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* Zinc oxide (ZnO) was selected as an additive to these composites because of previous studies (Ref. 15) in which ZnO was found to be an effective synergistic additive to resin bonded MoS_2 films. Furthermore, the melting point of ZnO is listed in handbooks to be over 1900°C (2173°K) whereas the melting point of Sb_2O_3 is listed at 656°C (929°K); this fact was considered to be important if the carbonizing temperature was extended to values near or above the melting point of Sb_2O_3.

TABLE V

FRICTION AND WEAR OF CARBONIZED CID-101 (3x) COMPOSITE SPECIMENS IN OSCILLATORY SLIDER TESTS

Running Time		Load		Speed		PV		Wear		Wear Factor			Average
						lb-ft	MNm			$(10^{-8}$ in.		10^{-17}	Friction
(min)	(ks)	(psi)	(MN/m^2)	(ft/min)	(m/s)	$in.^2$-min	m^2-sec	$(10^{-4}$ in.)	(μm)	$ft^{-1})$	$(10^{-9}$ m/m)	m^3/Nm	Coefficient
CID-101-61 Specimen,a/ carbonized at 400°C													
1,440	86.4	1,500	10.3	12	0.061	18,000	0.63	6.0	15.2	3.5	2.92	28.3	0.10
1,440	86.4	1,500	10.3	24	0.122	36,000	1.26	5.0	12.7	1.5	1.25	11.8	0.08
1,440	86.4	1,500	10.3	36	0.183	54,000	1.89	6.0	15.2	1.2	1.00	9.45	0.06
1,440	86.4	3,000	20.7	12	0.061	36,000	1.26	1.0	2.5	0.6	0.50	2.33	0.06
1,440	86.4	3,000	20.7	24	0.122	72,000	2.52	4.0	10.2	1.2	1.00	4.75	0.05
1,440	86.4	3,000	20.7	36	0.183	108,000	3.78	6.0	15.2	1.2	1.00	4.72	0.04
CID-101-69 Specimen, carbonized at 400°C													
1,444	86.6	6,000	41.4	3	0.015	18,000	0.63	7.0	17.8	16.2	13.49	33.2	0.08
1,440	86.4	6,000	41.4	9	0.046	54,000	1.89	6.3	16.0	4.9	4.08	9.94	0.06
2	0.1	12,000	82.7	3	0.015	36,000	1.26	b/	-	-	-	-	-
-	-	12,000	82.7	9	0.046	108,000	3.78	-	-	-	-	-	-
CID-101-75 Specimen, carbonized at 550°C													
1,449	86.9	6,000	41.4	3	0.015	18,000	0.63	16.7	42.4	38.42	32.00	78.6	0.08
1,441	86.5	6,000	41.4	9	0.046	54,000	1.89	5.7	14.5	4.40	3.67	9.01	0.06
15	0.9	12,000	82.7	3	0.015	36,000	1.26	b/	-	-	-	-	-
-	-	12,000	82.7	9	0.046	108,000	3.78	-	-	-	-	-	-

Note: CID-101, -61, -69 and -75 contain 18.6 (vol.) graphite fibers + MoS_2 + Sb_2O_3 in a phenolic resin matrix.

a/ Data for this specimen were reported earlier; see Ref. 15, Part IV.

b/ Test was terminated early because specimen crushed; wear measurements are not meaningful.

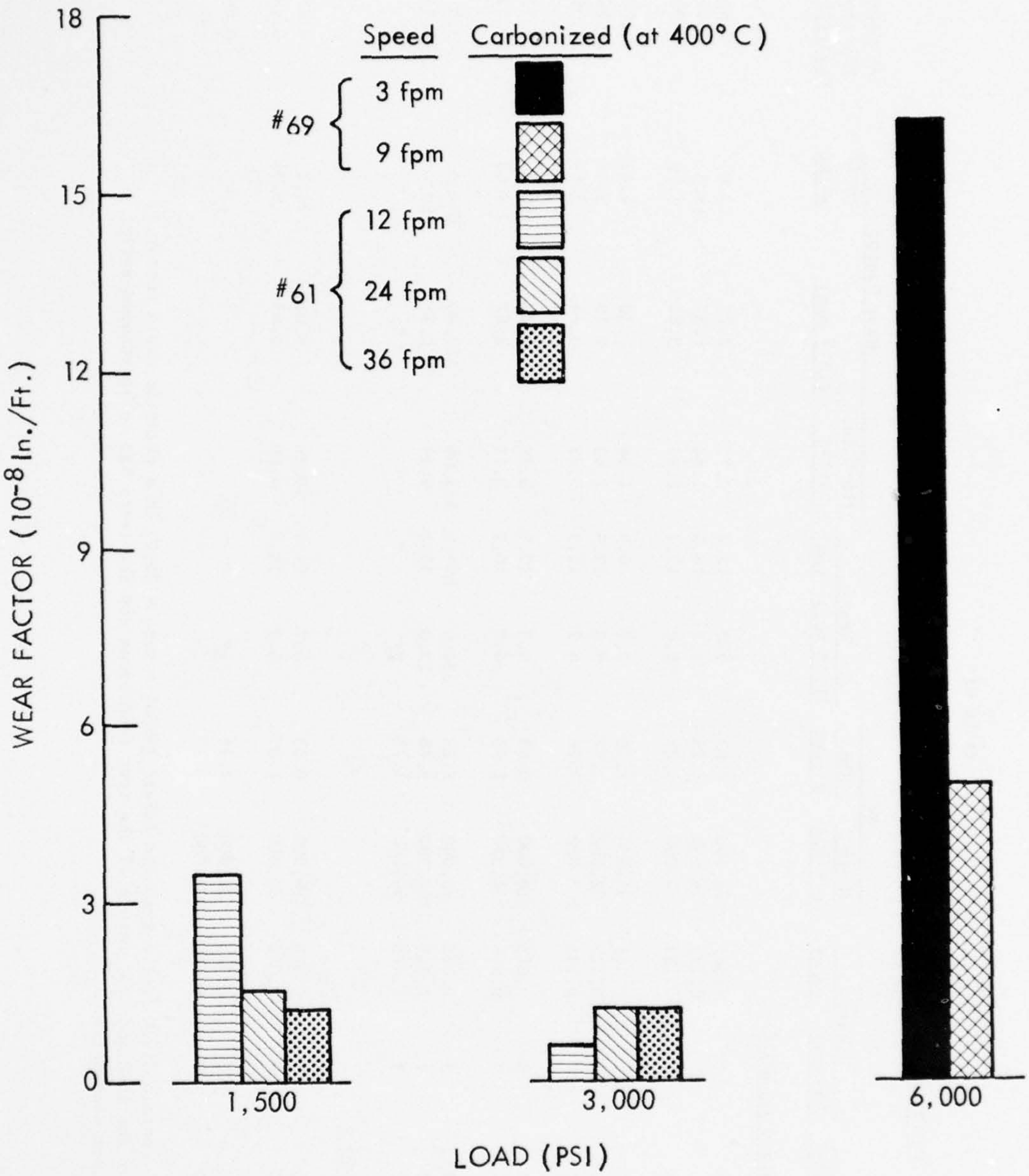

Figure 16 - Bar Graph Showing Wear Factor Versus Load for CID-101 (3x) Specimens in Slider Tests

TABLE VI

FRICTION AND WEAR OF CARBONIZED CID-101 (6x) COMPOSITES IN OSCILLATORY SLIDER TESTS

Running Time		Load		Speed		PV		Wear		Wear Factor			Average Friction Coefficient
(min)	(ks)	(psi)	(MN/m^2)	(ft/min)	(m/s)	lb-ft / in.^{2}-min	MNm / m^2-sec	(10^{-4} in.)	(μm)	(10^{-8} in. ft^{-1})	(10^{-9} m/m)	10^{-17} m^3/Nm	
CID-101-72 Specimen, carbonized at 400°C													
1,527	91.6	1,500	10.3	12	0.061	18,000	0.63	5.0	12.7	2.73	2.27	22.0	0.15
1,447	86.8	1,500	10.3	24	0.122	36,000	1.26	5.7	14.5	1.64	1.37	13.5	0.09
1,443	86.6	1,500	10.3	36	0.183	54,000	1.89	5.0	12.7	0.96	0.80	7.89	0.07
1,446	86.6	3,000	20.7	12	0.061	36,000	1.26	2.7	6.9	1.56	1.30	6.43	0.08
1,540	92.4	3,000	20.7	24	0.122	72,000	2.52	5.3	13.5	1.43	1.19	5.78	0.05
1,460	87.6	3,000	20.7	36	0.183	108,000	3.78	4.7	11.9	0.89	0.74	3.65	0.05
1,449	86.9	6,000	41.4	3	0.015	18,000	0.63	4.3	10.9	9.89	8.24	20.2	0.12
1,517	91.0	6,000	41.4	9	0.046	54,000	1.89	4.3	10.9	3.15	2.62	6.43	0.13
1,452	87.1	12,000	82.7	3	0.015	36,000	1.26	354.0	899.0	813.00	677.00	831.0	0.07
1,447	86.8	12,000	82.7	9	0.046	108,000	3.78	13.0	33.0	9.98	8.31	10.2	0.06
1	0.1	16,800	115.8	3	0.015	50,400	1.77	a/	-	-	-	-	-
CID-101-74, carbonized at 550°C													
1,440	86.4	6,000	41.4	3	0.015	18,000	0.63	4.7	11.9	10.88	9.06	22.2	0.17
1,440	86.4	6,000	41.4	9	0.046	54,000	1.89	6.3	16.0	4.86	4.05	9.94	0.10
1,360	81.6	12,000	82.7	3	0.015	36,000	1.26	a/	-	-	-	-	0.09
-	-	12,000	82.7	9	0.046	108,000	3.78	-	-	-	-	-	-

Note: CID-101, -72 and -74 contain 31.3% (vol.) graphite fibers (T-50) + MoS_2 + Sb_2O_3 in a phenolic resin matrix.

a/ This sample crushed under the load and temperature of the test conditions and the tests had to be stopped early; wear measurements are not meaningful.

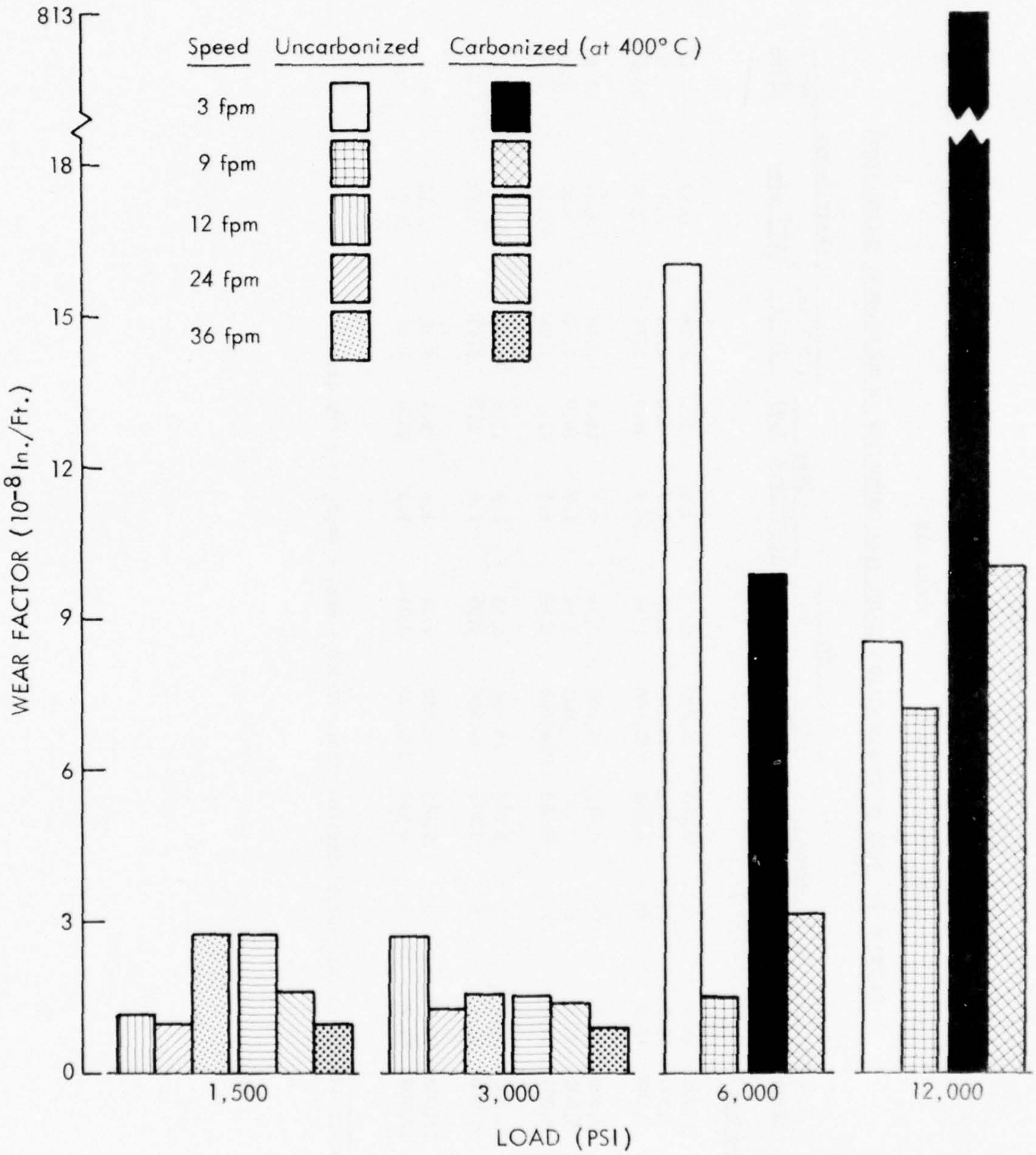

Figure 17 - Bar Graph Showing Wear Factor Versus Load for CID-101 (6x) Composites in Slider Tests

TABLE VII

FRICTION AND WEAR OF UNCARBONIZED CID-101 (6x) COMPOSITES IN OSCILLATORY SLIDER TESTS

Running Time		Load		Speed		PV		Wear		Wear Factor			Average
(min)	(ks)	(psi)	(MN/m^2)	(ft/min)	(m/s)	$\frac{lb\text{-}ft}{in.^2\text{-}min}$	$\frac{MN}{m\text{-}sec}$	(10^{-4} in.)	(μm)	(10^{-8} in. ft^{-1})	(10^{-9} m/m)	10^{-17} m^3/Nm	Friction Coefficient
CID-101-72 Specimen													
1,440	86	1,500	10.3	12	0.061	18,000	0.63	2.0	5.1	1.16	0.97	9.4	0.13
1,481	89	1,500	10.3	24	0.122	36,000	1.26	3.3	8.4	0.93	0.77	7.5	0.10
1,443	87	1,500	10.3	36	0.183	54,000	1.89	14.3	36.3	2.75	2.29	22.2	0.12
1,453	87	3,000	20.7	12	0.061	36,000	1.26	4.7	11.9	2.70	2.25	10.9	0.07
1,474	88	3,000	20.7	24	0.122	72,000	2.52	4.3	10.9	1.22	1.02	4.9	0.06
1,462	88	3,000	20.7	36	0.183	108,000	3.78	8.3	21.1	1.58	1.32	6.4	0.05
1,454	87	6,000	41.4	3	0.015	18,000	0.63	7.0	17.8	16.05	13.37	32.3	0.10
1,452	87	6,000	41.4	9	0.046	54,000	1.89	2.0	5.1	1.53	1.27	3.1	0.08
1,441	86	12,000	82.7	3	0.015	36,000	1.26	3.7	9.4	8.56	7.13	8.6	0.05
1,441	86	12,000	82.7	9	0.046	108,000	3.78	9.3	23.6	7.17	5.97	7.2	0.05

Note: CID-101-72 contains 31.4% (vol.) graphite fibers (T-50) + MoS_2 + Sb_2O_3 in a CPR matrix.

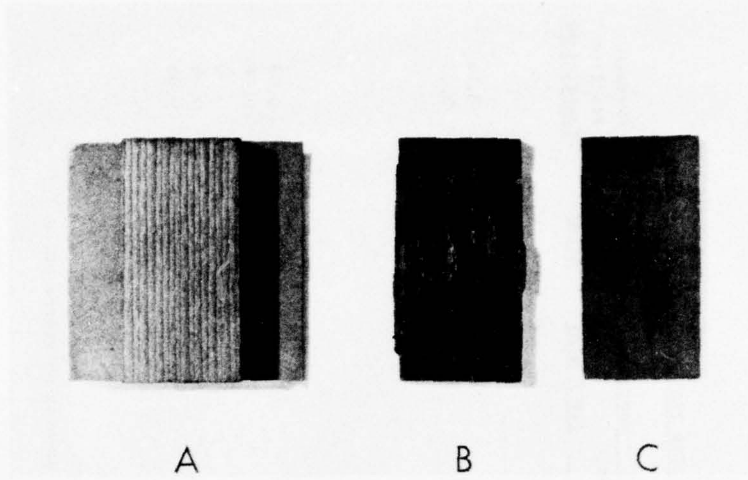

Figure 18 - Photographs of Oscillatory Slider Test Specimens; 1/2 x 1 in. (0.0127 x 0.0254 m) Sliding Surface. A is CID-101- (6X), carbonized, mounted, prior to test; B is CID-101-72 (6X), uncarbonized, after test; and C is CID-101-72 (6X), carbonized, after test.

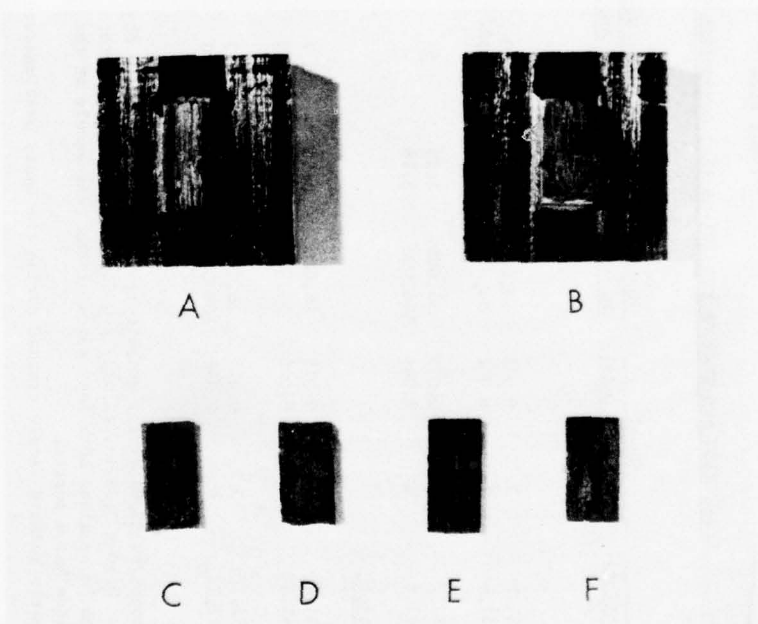

Figure 19 - Photographs of Oscillatory Slider Specimens After Testing; 1/4 x 1/2 in. (0.00635 x 0.0127 m) Sliding Surface. A is CID-101-86 (8X), carbonized; B is CID-111-3 (6X), carbonized; C is CID-101-72 (6X), uncarbonized; D is CID-101-72 (6X), carbonized; E is CID-111-3 (6X), uncarbonized; and F is CID-103-6 (6X), uncarbonized.

TABLE VIII

FRICTION AND WEAR OF CID-101-86 (8x) COMPOSITES IN OSCILLATORY SLIDER TESTS

Running Time (min)	Running Time (ks)	Load (psi)	Load (MN/m^2)	Speed (ft/min)	Speed (m/s)	PV lb-ft/$in.^2$-min	PV MNm/m^2-sec	Wear (10^{-4} in.)	Wear (μm)	Wear Factor (10^{-8} in./ft^{-1})	Wear Factor (10^{-9} m/m)	Wear Factor 10^{-17} m^3/Nm	Average Friction Coefficient
Specimen Uncarbonized													
1,463	87.8	6,000	41.4	3	0.015	18,000	0.63	1.3	3.3	2.96	2.47	6.06	0.14
1,446	86.8	6,000	41.4	9	0.046	54,000	1.89	5.7[a]	14.5	4.38	3.65	8.97	0.13
11	0.7	12,000	82.7	3	0.015	36,000	1.26	[b]	-	-	-	-	-
-	-	12,000	82.7	9	0.046	108,000	3.78	-	-	-	-	-	-
Specimen Carbonized at 400°C													
1,459	87.5	6,000	41.4	3	0.015	18,000	0.63	6.7	17.0	15.31	12.75	31.3	0.09
1,484	89.0	6,000	41.4	9	0.046	54,000	1.89	6.0	15.2	4.49	3.74	9.17	0.06
1,442	86.5	12,000	82.7	3	0.015	36,000	1.26	4.3	10.9	9.94	8.28	10.2	0.04
1,446	86.8	12,000	82.7	9	0.046	108,000	3.78	6.0	15.2	4.61	3.84	4.70	0.03

Note: CID-101-86 (8x) contains 37.8% (vol.) graphite fibers (T-50) + MoS_2 + Sb_2O_3 in a CPR matrix.
Test Sample Size: 0.50 x 0.25 in. (0.0127 x 0.00635 m). Stroke length: 1.0 in. (0.0254 m).

a/ Small chips had broken loose along both long edges of the test sample at the end of this test; however no appreciable change in surface area has occurred.

b/ Test was terminated early because sample crushed during the test; wear measurements are not meaningful.

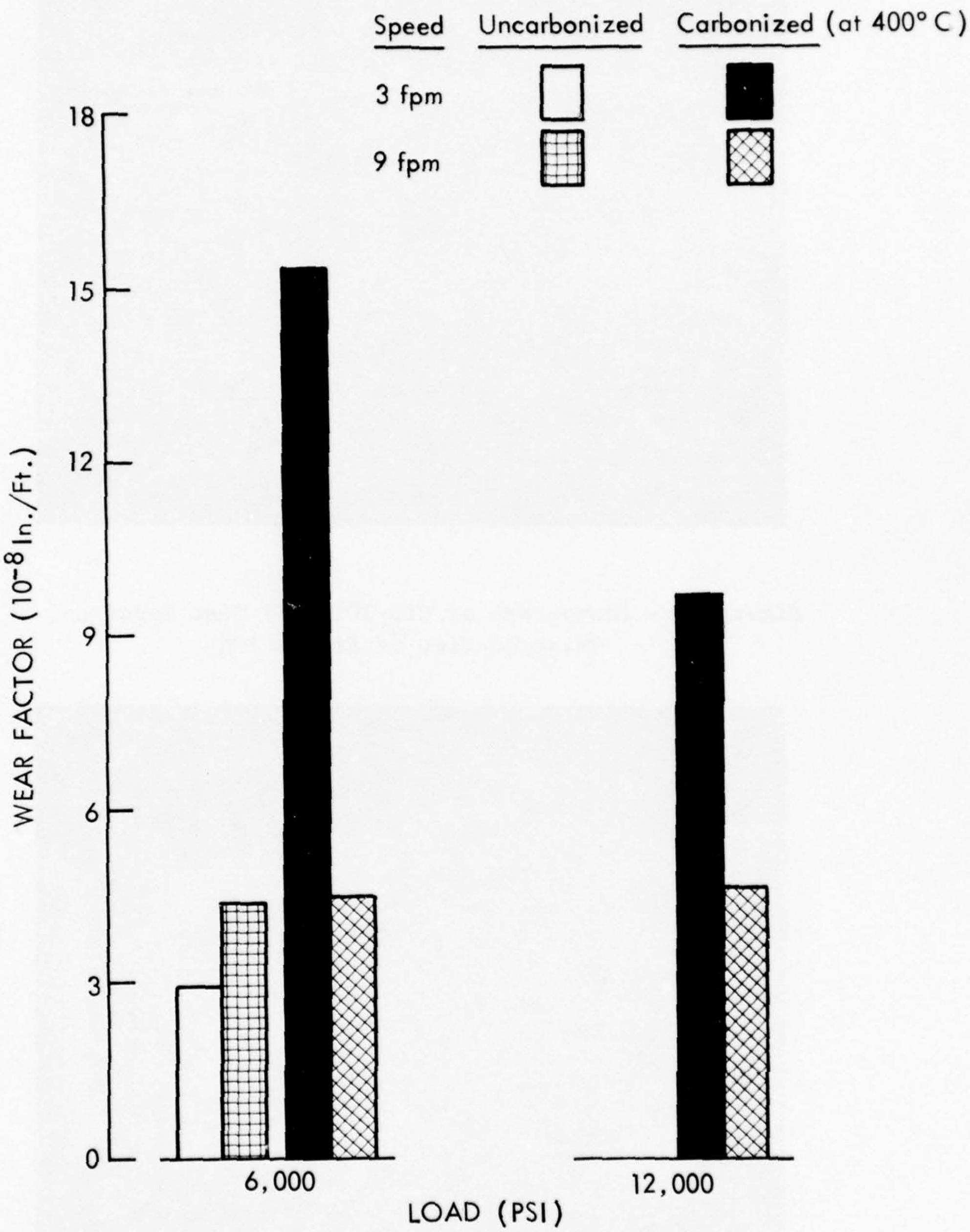

Figure 20 - Bar Graph Showing Wear Factor Versus Load for CID-101 (8x) Composites in Slider Tests

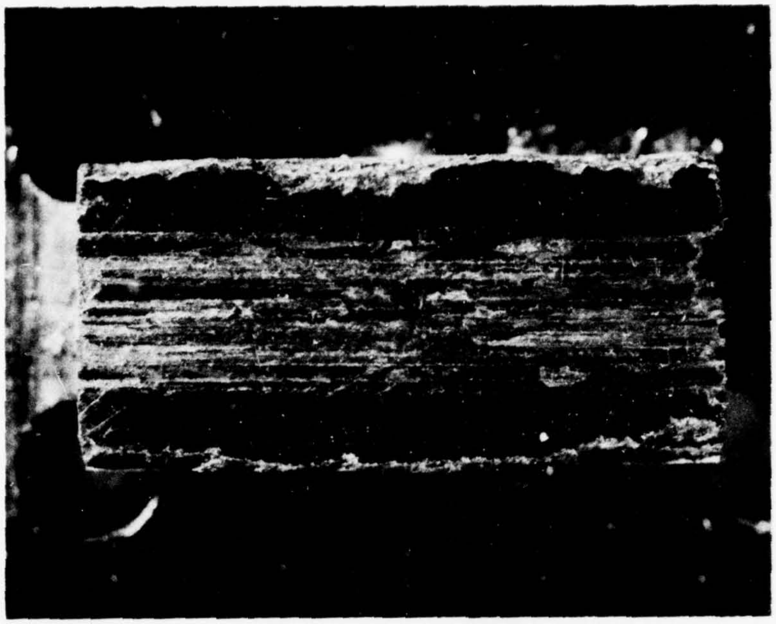

Figure 21 - Photograph of CID-101 (8X) Test Specimen,
Enlarged View of Figure 19A

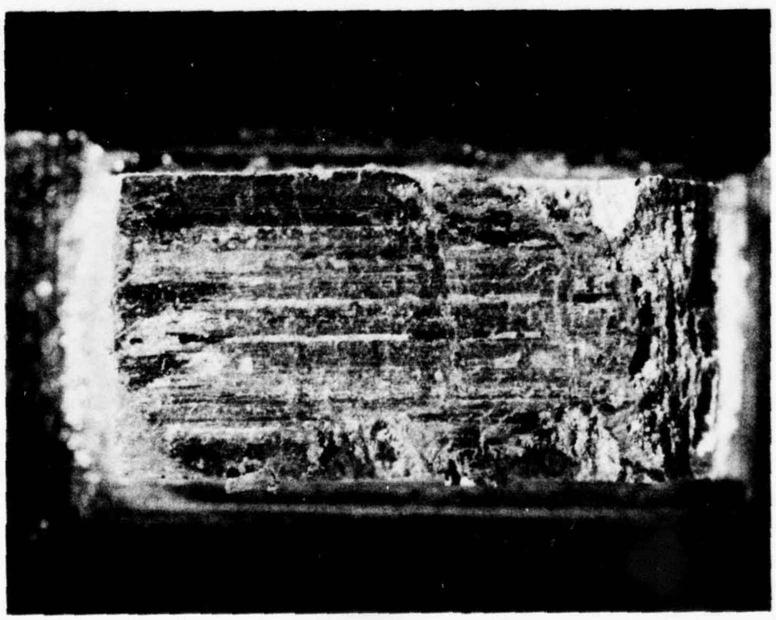

Figure 22 - Photograph of CID-111-3 (6X) Test Specimen,
Enlarged View of Figure 19B

Data for the carbonized specimens with 18.6% fibers are summarized in Table IX. Consistently low wear rates were measured for loads of 1,500 and 3,000 psi (10.3 and 20.7 MN/m^2). However, the specimen failed in less than an hour at a load of 6,000 psi (41.4 MN/m^2).

Data for both the uncarbonized and carbonized specimens with 31.3% fibers are summarized in Table X. The uncarbonized specimens (see Figure 19) functioned satisfactorily at the two high loads of 6,000 and 12,000 psi (41.4 and 82.7 MN/m^2). The carbonized specimen failed after 2 hr (7.2 ks) at the high-load, low-speed conditions. These wear factors are slightly higher than for corresponding specimens of the CID-101 composition.

c. CID-111 composites are prepared as mixtures of MoS_2, Sb_2O_3, PTFE,* and graphite fibers in a phenolic resin matrix. Screening friction and wear tests have been conducted on specimens containing three different quantities of PTFE, each with approximately 30% fibers.

Data are summarized in Table XI for specimens containing 2% PTFE. The lowest wear and friction coefficients were measured for the uncarbonized specimen which satisfactorily completed the 12,000 psi (82.7 MN/m^2) tests but failed after 4 hr (14.9 ks) at 15,000 psi (103.4 MN/m^2) at the slow speed. The wear for specimens carbonized at 400°C (673°K) shown in Figure 22, were within a factor of two of the values for the uncarbonized specimen. The specimens that were carbonized at 320°C, however, failed during the high-load, high-speed test (62% complete). The wear factors are shown graphically as a function of load in Figure 23.

Screening friction and wear data for CID-111 composites which contained 4% PTFE and were carbonized at 320°C (593°K) are summarized in Table XII. These specimens exhibited consistently low wear and friction coefficients in tests conducted at both speeds and at loads of 6,000 and 9,600 psi (41.4 and 66.2 MN/m^2). At the high load of 12,000 psi (82.7 MN/m^2) this specimen exhibited low friction and wear at the low speed, but failed quickly at the high speed.

Screening data for CID-111 composites containing 7.7% PTFE and carbonized at 320°C (593°K) are shown in Table XIII. The wear factors are particularly low for these specimens at loads of 1,500 and 3,000 psi (10.3 and 20.7 MN/m^2) and the three speeds employed.

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* Polytetrafluroethylene (PTFE) was selected as an additive primarily to utilize its low shear strength and flow characteristics to reduce the friction in stop-start conditions at the ends of oscillatory sliding. The formulations were designed to find the minimum amount of PTFE which would provide the desired lubrication characteristics so as to minimize the anticipated degradation in structural properties.

TABLE IX

FRICTION AND WEAR OF CARBONIZED CID-103-2 (3x) COMPOSITES IN OSCILLATORY SLIDER TESTS

Running Time		Load		Speed		PV		Wear		Wear Factor			Average Friction Coefficient
(min)	(ks)	(psi)	(MN/m^2)	(ft/min)	(m/s)	$\frac{lb\text{-}ft}{in.^2\text{-}min}$	$\frac{MNm}{m^2\text{-}sec}$	(10^{-4} in.)	(μm)	(10^{-8} in. ft^{-1})	(10^{-9} m/m)	10^{-17} m^3/Nm	
1,440	86.4	1,500	10.3	12	0.061	18,000	0.63	7.3	18.5	4.22	3.52	34.5	0.15
1,446	86.8	1,500	10.3	24	0.122	36,000	1.26	10.3	26.2	2.97	2.47	24.3	0.09
1,459	87.5	1,500	10.3	36	0.183	54,000	1.89	9.3	23.6	1.77	1.47	14.5	0.07
1,453	87.2	3,000	20.7	12	0.061	36,000	1.26	6.7	17.0	3.84	3.20	15.7	0.08
1,446	86.8	3,000	20.7	24	0.122	72,000	2.52	6.0	15.2	1.73	1.44	7.05	0.05
1,440	86.4	3,000	20.7	36	0.183	108,000	3.78	11.7	29.7	2.26	1.88	9.23	0.04
47	2.8	6,000	41.4	3	0.015	18,000	0.63	a/	-	-	-	-	-

Note: CID-103-2 (3x) contains 18.6% (vol.) graphite fibers (T-50) + MoS_2 + ZnO in a CPR matrix.
a/ Test was terminated early because sample flowed out during the test; wear measurements are not meaningful.

TABLE X

FRICTION AND WEAR OF CID-103 (6x) COMPOSITES IN OSCILLATORY SLIDER TESTS

Running Time (min)	Running Time (ks)	Load (psi)	Load (MN/m^2)	Speed (ft/min)	Speed (m/s)	PV $\frac{lb\text{-}ft}{in.^2\text{-}min}$	PV $\frac{MNm}{m^2\text{-}sec}$	Wear (10^{-4} in.)	Wear (µm)	Wear Factor (10^{-8} in. ft^{-1})	Wear Factor (10^{-9} m/m)	Wear Factor 10^{-17} m^3/Nm	Average Friction Coefficient
Uncarbonized Specimen (CID-103-6)													
1,488	89.3	6,000	41.4	3	0.015	18,000	0.63	11.7	29.7	26.21	21.83	53.6	0.19
1,510	90.6	6,000	41.4	9	0.046	54,000	1.89	9.0	22.9	6.62	5.51	13.6	0.14
1,450	87.0	12,000	82.7	3	0.015	36,000	1.26	7.7	19.6	17.70	14.74	18.1	0.16
1,445	86.7	12,000	82.7	9	0.046	108,000	3.78	13.0	33.0	10.00	8.33	10.2	0.09
Carbonized Specimen (CID-103-5)													
1,443	86.6	1,500	10.3	12	0.061	18,000	0.63	17.0	43.2	9.82	8.18	79.4	0.22
1,441	86.5	1,500	10.3	24	0.122	36,000	1.26	12.7	32.3	3.57	2.97	29.7	0.16
1,440	86.4	1,500	10.3	36	0.183	54,000	1.89	14.7	37.3	2.84	2.37	22.9	0.10
1,460	87.6	3,000	20.7	12	0.061	36,000	1.26	9.7	24.6	5.54	4.61	22.2	0.14
1,445	86.7	3,000	20.7	24	0.122	72,000	2.52	14.0	35.6	4.04	3.37	16.3	0.08
1,469	88.1	3,000	20.7	36	0.183	108,000	3.78	19.0	48.3	3.59	2.99	14.5	0.06
1,440	86.4	6,000	41.4	3	0.015	18,000	0.63	5.0	12.7	11.57	9.64	23.7	0.08
1,446	86.8	6,000	41.4	9	0.046	54,000	1.89	7.7	19.6	5.92	4.93	11.9	0.06
120	7.2	12,000	82.7	3	0.015	36,000	1.26	a/	-	-	-	-	0.08

Note: CID-103 (6x) specimens contain 31.3% (vol.) graphite fibers + MoS_2 + ZnO in a phenolic resin matrix. Test Sample Size: 0.50 x 0.25 in. (0.0127 x 0.00635 m). Stroke length: 1.0 in. (0.0254 m).

a/ Test was terminated early because specimen crushed; wear measurements are not meaningful.

TABLE XI

FRICTION AND WEAR OF CID-111-3 (6x) COMPOSITES IN OSCILLATORY SLIDER TESTS

Running Time		Load		Speed		PV		Wear		Wear Factor			Average Friction Coefficient
(min)	(ks)	(psi)	(MN/m^2)	(ft/min)	(m/s)	$\frac{lb\text{-}ft}{in.^2\text{-}min}$	$\frac{MNm}{m^2\text{-}sec}$	(10^{-4} in.)	(μm)	(10^{-8} in. ft^{-1})	(10^{-9} m/m)	10^{-17} m^3/Nm	
Uncarbonized Specimen													
1,446	86.8	6,000	41.4	3	0.015	18,000	0.63	2.3	5.8	5.30	4.41	10.8	0.08
1,449	86.9	6,000	41.4	9	0.046	54,000	1.89	2.7	6.9	2.07	1.72	4.26	0.05
1,496	89.8	12,000	82.7	3	0.015	36,000	1.26	1.7	4.3	3.79	3.16	3.86	0.04
1,440	86.4	12,000	82.7	9	0.046	108,000	3.78	4.7	11.9	3.63	3.02	3.70	0.03
249	14.9	15,000	103.4	3	0.015	45,000	1.58	a/	-	-	-	-	-
Specimen Carbonized at 320°C (593°K)													
1,447	86.8	6,000	41.4	3	0.015	18,000	0.63	2.3	5.0	5.30	4.41	10.8	0.16
1,480	88.8	6,000	41.4	9	0.046	54,000	1.89	2.0	5.1	1.50	1.25	3.08	0.08
1,440	86.4	12,000	82.7	3	0.015	36,000	1.26	5.0	12.7	11.57	9.64	11.8	0.10
900	54.0	12,000	82.7	9	0.046	108,000	3.78	a/	-	-	-	-	0.07
Specimen Carbonized at 400°C (673°K)													
1,468	88.1	6,000	41.4	3	0.015	18,000	0.63	3.3	8.4	7.49	6.24	15.4	0.18
1,470	88.2	6,000	41.4	9	0.046	54,000	1.89	2.0	5.1	1.51	1.26	3.10	0.09
1,440	86.4	12,000	82.7	3	0.015	36,000	1.26	4.3	10.9	9.95	8.29	10.2	0.10
1,460	87.6	12,000	82.7	9	0.046	108,000	3.78	5.0 b/	12.7	3.81	3.17	3.89	0.05

Note: CID-111-3 contains 2.0% (vol.) PTFE added to the CID-101 (6x) composition. Test sample size: 0.50 x 0.25 in. (0.0127 x 0.00635 m). Stroke length: 1.0 in. (0.0254 m).

a/ Test was terminated early because sample crushed during the test; wear measurements are not meaningful.

b/ Average value of wear at only two locations (versus three normally) because of chipping at one end of the test specimen.

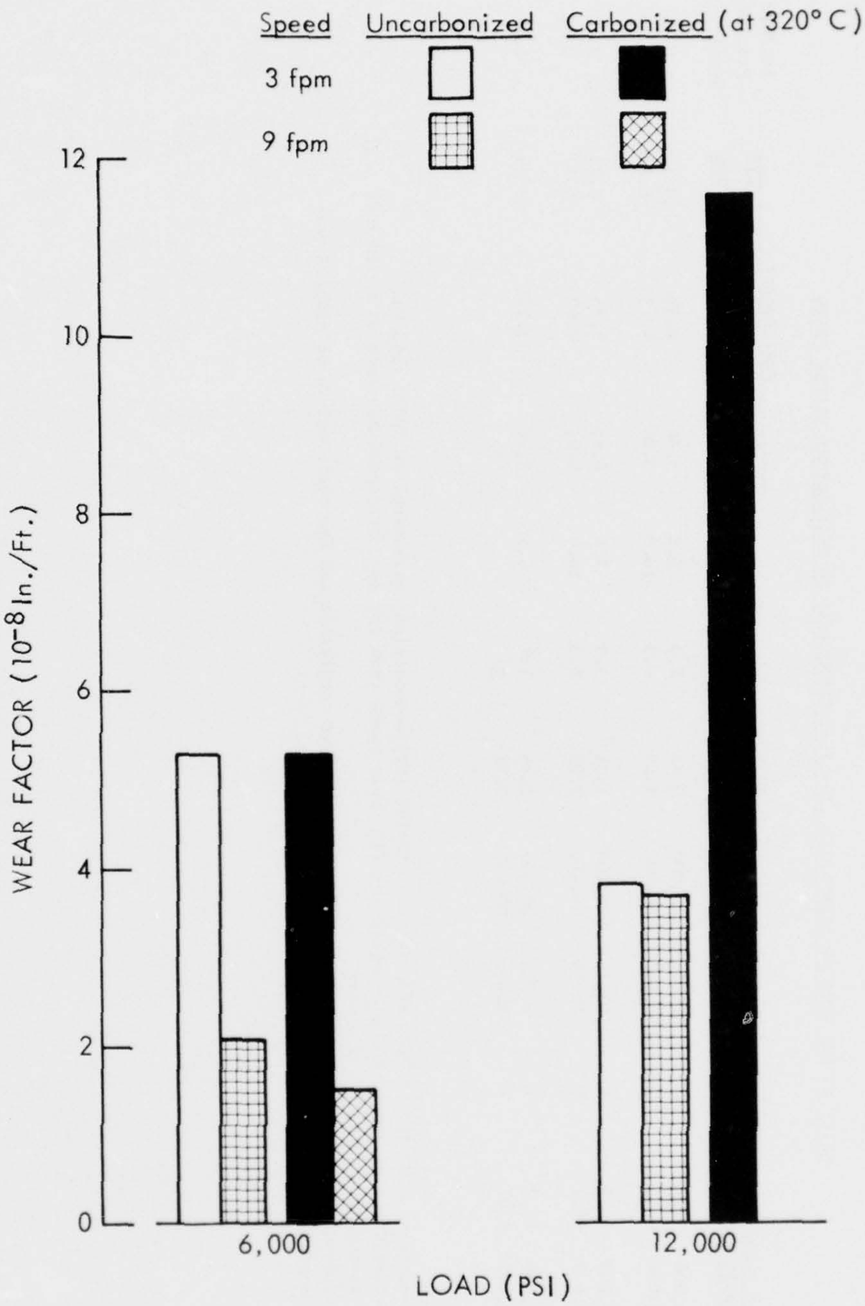

Figure 23 - Bar Graph Showing Wear Factor Versus Load for ClD-111-3 (6x) Composites in Slider Tests

TABLE XII

FRICTION AND WEAR OF CARBONIZED CID-111-2 COMPOSITES IN OSCILLATORY SLIDER TESTS

Running Time		Load		Speed		PV		Wear		Wear Factor			Average Friction Coefficient
(min)	(ks)	(psi)	(MN/m^2)	(ft/min)	(m/s)	$\frac{lb\text{-}ft}{in.^2\text{-}min}$	$\frac{MNm}{m^2\text{-}sec}$	(10^{-4} in.)	(μm)	(10^{-8} in. ft^{-1})	(10^{-9} m/m)	10^{-17} m^3/Nm	
1,458	87.5	6,000	41.4	3	0.015	18,000	0.63	2.3	5.8	5.26	4.38	10.7	0.17
1,458	87.5	6,000	41.4	9	0.046	54,000	1.89	4.3	10.9	3.28	2.73	6.69	0.08
1,446	86.8	9,600	66.2	3	0.015	28,800	1.01	3.0	7.6	6.92	5.76	8.82	0.10
1,451	87.1	9,600	66.2	9	0.046	86.400	3.03	6.3	16.0	4.82	4.02	6.17	0.06
1,445	86.7	12,000	82.7	3	0.015	36,000	1.26	1.7	4.3	3.92	3.27	3.99	0.08
8	0.5	12,000	82.7	9	0.046	108,000	3.78	a/	-	-	-	-	-

Note: CID-111-2 contains 4.0% (vol.) PTFE added to the CID-101 (6x) composition; carbonized at 320°C (593°K). The friction trace was found to be smoother for all these tests than for any corresponding tests with CID-100, -101, or -103 specimens.

a/ These samples flowed out under the load and temperature of the test conditions and the tests had to be stopped very early; wear measurements are not meaningful.

TABLE XIII

FRICTION AND WEAR OF CARBONIZED CID-111-1 COMPOSITES IN OSCILLATORY SLIDER TESTS

Running Time		Load		Speed		PV		Wear		Wear Factor			Average Friction Coefficient
(min)	(ks)	(psi)	(MN/m^2)	(ft/min)	(m/s)	lb-ft/in.^{2}-min	MNm/m^2-sec	(10^{-4} in.)	(μm)	(10^{-8} in. ft^{-1})	(10^{-9} m/m)	10^{-17} m^3/Nm	
1,447	86.8	1,500	10.3	12	0.061	18,000	0.63	4.3	10.9	2.48	2.07	20.2	0.16
1,454	87.2	1,500	10.3	24	0.122	36,000	1.26	4.3	10.9	1.23	1.02	10.1	0.12
1,500	90.0	1,500	10.3	36	0.183	54,000	1.89	6.7	17.0	1.24	1.03	10.1	0.10
1,455	87.3	3,000	20.7	12	0.061	36,000	1.26	1.7	4.3	0.974	0.811	3.97	0.08
1,452	87.1	3,000	20.7	24	0.122	72,000	2.52	3.7	9.4	1.06	0.883	4.34	0.07
1,452	87.1	3,000	20.7	36	0.152	108,000	3.78	3.7	9.4	0.708	0.590	2.90	0.05
1,480	88.8	6,000	41.4	3	0.015	18,000	0.63	9.3	23.6	20.94	17.44	42.8	0.16
1,452	87.1	6,000	41.4	9	0.046	54,000	1.89	6.0	15.2	4.59	3.82	9.37	0.10
1,442	86.5	9,600	66.2	3	0.015	28,000	1.01	2.7	6.9	6.24	5.20	8.04	0.12
1,440	86.4	9,600	66.2	9	0.046	86,400	3.03	1.3	3.3	1.00	0.833	1.28	0.06
11	0.7	12,000	82.7	3	0.015	36,000	1.26	a/	-	-	-	-	-

Note: CID-111-1 contains 7.7% (vol.) PTFE added to the CID-101 (6x) composition; carbonized at 320°C (593°K). The friction trace was found to be smoother for all these tests than for any corresponding tests with CID-100, -101, or -103 specimens.

a/ These samples flowed out under the load and temperature of the test conditions and the tests had to be stopped very early; wear measurements are not meaningful.

Similarly the wear factors are low at both speeds used in the 9,600 psi (66.2 MN/m^2) tests and in the high speed test at 6,000 psi (41.4 MN/m^2). The wear factor for the latter load at low speed was more than four times as great as at the higher speed and represents the highest wear factor recorded for any of the CID-111 composites. The wear factor dependence on speed seems to be typical of the carbonized phenolic resin composites at the higher loads. This CID-111 composite failed quickly at the high load of 12,000 psi (82.7 MN/m^2). Comparative data for an uncarbonized specimen of CID-111 containing 7.7% PTFE are shown in Table XIV. The wear factors of the uncarbonized specimen tend to be higher at all test conditions than those of the carbonized specimen.

d. CID-661 composites were prepared with MoS_2 and ZnO powders and chopped graphite fibers dispersed in a polyphenylene sulfide resin matrix. Screening friction and wear data for an uncarbonized specimen are shown in Table XV. The wear factors are quite high for both speeds at 6,000 psi (41.4 MN/m^2). This specimen failed at double that load after completing only 13% of the scheduled test. A specimen of this composition was carbonized at 550°C (823°K) and scheduled for screening friction and wear tests. However, the material was so soft and weak that a suitable test specimen could not be prepared. A commercial specimen consisting of MoS_2 + Sb_2O_3 + PTFE in a PPS matrix, which is labeled PPS-40 in this report, sustained a load of 15,000 psi (103.4 MN/m^2) at the low speed for 18 min (1.1 ks) before crushing.

e. CID-1101 composites incorporate chopped glass fiber and powders of MoS_2 and Sb_2O_3 in a phenolic resin matrix. Screening friction and wear data of four such specimens are shown in Table XVI. Specimen -1 of this composition was uncarbonized and survived 7 hr (25.6 ks) in oscillatory slider tests at 15,000 psi (103.4 MN/m^2) and 3 fpm (0.015 m/s), although the wear factor was high. Two specimens which were carbonized while under pressure in the die failed quickly at the high test load. Also shown in Table XVI are data for a fourth specimen, carbonized at 800°F (700°K) while under pressure in a die, which failed in 14.5 hr (52.6 ks) of oscillatory sliding at 6,000 psi (41.4 MN/m^2).

f. Various exploratory composites which incorporate graphite fibers plus other additives in phenolic resin matrices have been tested.

Screening friction and wear data have been obtained on the oscillatory slider test rig with specimens containing the highest concentration of fibers prepared to date in the uncarbonized form. Screening friction data shown in Table XVII were obtained with samples of specimen CID-201-1 which contains 44.4% graphite fibers and Sp-1 which contains 59.1% graphite fibers. As shown in Table XVII, the uncarbonized samples performed well at 6,000 psi (41.4 MN/m^2), but failed quickly at 12,000 psi (82.7 MN/m^2).

TABLE XIV

FRICTION AND WEAR OF UNCARBONIZED CID-111-1 COMPOSITES IN OSCILLATORY SLIDER TESTS

Running Time		Load		Speed		PV		Wear		Wear Factor			Average Friction
(min)	(ks)	(psi)	(MN/m^2)	(ft/min)	(m/s)	lb-ft / $in.^2$-min	MNm / m^2-sec	(10^{-4} in.)	(μm)	(10^{-8} in. ft^{-1})	(10^{-9} m/m)	10^{-17} m^3/Nm	Coefficient
1,440	86.4	1,500	10.3	12	0.061	18,000	0.63	11.7	29.7	6.77	5.64	55.4	0.14
1,442	86.5	1,500	10.3	24	0.122	36,000	1.26	20.0	50.8	5.78	4.81	47.3	0.13
1,485	89.1	1,500	10.3	36	0.183	54,000	1.89	17.7	45.0	3.31	2.76	27.1	0.11
1,440	86.4	3,000	20.7	12	0.061	36,000	1.26	8.3	21.1	4.80	4.00	19.7	0.10
1,440	86.4	3,000	20.7	24	0.122	72,000	2.52	8.3	21.1	2.40	2.00	9.83	0.07
1,442	86.5	3,000	20.7	30	0.152	90,000	3.15	11.0	27.9	2.54	2.12	10.4	0.05
20	1.2	3,000	20.7	36	0.183	108,000	3.78	a/	-	-	-	-	0.10
1,440	86.4	6,000	41.4	3	0.015	18,000	0.63	14.0	35.6	32.4	26.99	66.4	0.13
1,444	86.6	6,000	41.4	9	0.046	54,000	1.89	9.3	23.6	7.16	5.96	14.6	0.08
4	0.2	12,000	82.7	9	0.046	108,000	3.78	a/	-	-	-	-	-

Note: CID-111-1 contains 7.7% (vol.) PTFE added to the CID-101 (6x) composition. The friction trace was found to be smoother for all these tests for any corresponding tests with CID-100, -101, or -103 specimens.

a/ These samples flowed out under the test conditions and the tests had to be stopped very early; wear measurements are not meaningful.

TABLE XV

FRICTION AND WEAR OF UNCARBONIZED PPS MATRIX COMPOSITES IN OSCILLATORY SLIDER TESTS

Running Time		Load		Speed		PV		Wear		Wear Factor			Average Friction Coefficient
(min)	(ks)	(psi)	(MN/m^2)	(ft/min)	(m/s)	$\frac{lb\text{-}ft}{in.^2\text{-}min}$	$\frac{MNm}{m^2\text{-}sec}$	(10^{-4} in.)	(μm)	(10^{-8} in. ft^{-1})	(10^{-9} m/m)	10^{-17} m^3/Nm	
CID-661-1 (6x)													
1,455	87.3	6,000	41.4	3	0.015	18,000	0.63	26.7	67.8	61.2	51.0	125.0	0.18
1,490	89.4	6,000	41.4	9	0.046	54,000	1.89	24.0	61.0	17.9	14.9	35.8	0.11
192	11.5	12,000	82.7	3	0.015	36,000	1.26	a/	-	-	-	-	0.05
-	-	12,000	82.7	9	0.046	108,000	3.78	-	-	-	-	-	-
PPS-40													
18	1.1	15,000	103.4	3	0.015	45,000	1.58	a/	-	-	-	-	-

Note: CID-661-1 contains 31.4% (vol.) graphite fibers + MoS_2 + ZnO in a polyphenylene sulfide resin matrix; this specimen was not carbonized. Test sample size: 0.50 x 0.25 in. (0.0127 x 0.00635). Stroke length: 1.0 in. (0.0254 m).

a/ These samples flowed out under the load and temperature of the test conditions and the tests had to be stopped very early; wear measurements are not meaningful.

TABLE XVI

OSCILLATORY SLIDER TEST DATA FOR CID-1101 SPECIMENS CARBONIZED AT DIFFERENT TEMPERATURES

Running Time		Load		Speed		PV		Wear		Wear Factor			Average Friction Coefficient
(min)	(ks)	(psi)	(MN/m^2)	(ft/min)	(m/s)	$\frac{lb\text{-}ft}{in.^2\text{-}min}$	$\frac{MNm}{m^2\text{-}sec}$	(10^{-4} in.)	(μm)	(10^{-8} in. ft^{-1})	(10^{-9} m/m)	10^{-17} m^3/Nm	
CID-1101-1													
426	25.6	15,000	103.4	3	0.015	45,000	1.58	14	35.6	109.55	91.26	89.7	0.11-0.16
CID-1101-2													
8	0.5	15,000	103.4	3	0.015	45,000	1.58	a/	-	-	-	-	0.19-0.25
CID-1101-3													
1	0.1	15,000	103.4	3	0.015	45,000	1.58	a/	-	-	-	-	-
CID-1101-4													
876	52.6	6,000	41.4	3	0.015	18,000	0.63	a/	-	-	-	-	0.15-0.26

Note: CID-1101 specimens contain 31% (vol.) glass fibers + MoS_2 + Sb_2O_3 in a CPR matrix; CID-1101-1 was uncarbonized; CID-1101-2, -3, and -4 were carbonized at 600, 700, and 800°F (588. 643, and 700°K) while under pressure in the die.

a/ Test was terminated early because sample crushed during the test; wear measurements are not meaningful.

TABLE XVII

FRICTION AND WEAR OF TWO UNCARBONIZED COMPOSITES IN OSCILLATORY SLIDER TESTS

Running Time		Load		Speed		PV		Wear		Wear Factor			Average Friction Coefficient
(min)	(ks)	(psi)	(MN/m^2)	(ft/min)	(m/s)	$\frac{lb\text{-}ft}{in.^2\text{-}min}$	$\frac{MNm}{m^2\text{-}sec}$	(10^{-4} in.)	(μm)	(10^{-8} in. ft^{-1})	(10^{-9} m/m)	10^{-17} m^3/Nm	
CID-201-1 (8x) uncarbonized													
1,440	86.4	6,000	41.4	3	0.015	18,000	0.63	3.3	8.4	7.64	6.36	15.7	0.05
-	-	6,000	41.4	9	0.046	54,000	1.89	-	-	-	-	-	-
136	8.2	12,000	82.7	3	0.015	36,000	1.26	a/	-	-	-	-	0.05
-	-	12,000	82.7	9	0.046	108,000	3.78	-	-	-	-	-	-
SP-1 (10x) uncarbonized													
1,442	86.5	6,000	41.4	3	0.015	18,000	0.63	6.0	15.2	13.87	11.55	28.3	0.26
-	-	6,000	41.4	9	0.046	54,000	1.89	-	-	-	-	-	-
105	6.3	12,000	82.7	3	0.015	36,000	1.26	a/	-	-	-	-	0.18
-	-	12,000	82.7	9	0.046	108,000	3.78	-	-	-	-	-	-

Note: CID-201-1 (8x) contains 44.4% (vol.) graphite fibers (T-50) + MoS_2 + Sb_2O_3 in a CPR matrix; SP-1 (10x) contains 59.1% (vol.) graphite fibers (T-50) in a phenolic resin matrix. Test sample size: 0.25 x 0.25 in. (0.00635 x 0.00635 m). Stroke length: 1.0 in. (0.0254 m).

a/ Test was terminated early because sample crushed during the test; wear measurements are not meaningful.

Data from similar tests with carbonized portions of five specimens are shown in Table XVIII. The carbonized CID-201 sample completed the test at 6,000 psi (41.4 MN/m^2), but failed quickly at 12,000 psi (82.7 MN/m^2). The wear factor at the lower load is more than four times the value shown in Table XVIII for an uncarbonized portion of the same specimen. The carbonized specimen of Sp-1 failed quickly at 15,000 psi (103.4 MN/m^2). Also shown in Table XVIII are data for two CID-101-L specimens which contain longer graphite fibers (0.75 in.; 0.019 m) and were carbonized at 315°C (588°K) while still under pressure in the die. One of three specimens run at 6,000 psi (41.4 MN/m^2) completed the scheduled test and the wear factor was comparatively high. The one specimen failed quickly when tested at 12,000 psi (82.7 MN/m^2). One carbonized specimen of CID-121-1, which contains BCM and graphite powders plus 18% graphite fibers in a phenolic resin matrix, failed quickly when tested at 15,000 psi (82.7 MN/m^2).

2. Special screening test results have been obtained in oscillatory sliding of constrained specimens in a flat-on-flat configuration. The specimens, shown in Figures 24 and 25, were compressed in steel cylinders during the polymerization cycle. Subsequently, the steel sleeve was machined back a short distance from one face and the extruding composite was tapered at 45 degrees to a 1/4 in. diameter (0.00635 m) flat end face. The tapered structure at the edge of the composite sliding interface would likely reduce errosion of the contact area by fracture (or chipping) during a test. Furthermore, residual radial compressive loads from the steel sleeve might be influencial in reducing wear of the composite. Three composite specimens were subjected to these special screening tests as shown in Table XIX. One specimen, which contained glass fiber in place of the graphite fiber, failed at the lowest load used in this test series and is not discussed further. The other two specimens sustained much higher loads and are discussed under separate subheadings.

a. CID-111-6 composite specimens contain MoS_2 + Sb_2O_3 + PTFE + graphite fibers in a phenolic resin matrix. The oscillatory sliding data for these sheathed, tapered, uncarbonized specimens are summarized in Table XIX. Consistently low wear was observed in 3 to 4 hr (10.8 to 14.4 ks) tests at loads from 12,000 to 24,000 psi (82.7 to 165.5 MN/m^2) and a speed of 3 fpm (0.015 m/s). The wear factor, shown graphically in Figure 26, increased by a factor of 2-1/2 at 27,450 psi (189.3 MN/m^2), which is the highest load capacity of the test device (for the contact area of these specimens). The average friction coefficient in these tests ranged from 0.06 at the low load to 0.04 at the higher loads. No evidence of cracking, chipping or fracture was found in examining the specimen after the test.

TABLE XVIII

FRICTION AND WEAR OF FIVE CARBONIZED COMPOSITES IN OSCILLATORY SLIDER TESTS

Running Time		Load		Speed		PV		Wear		Wear Factor			Average Friction Coefficient
(min)	(ks)	(psi)	(MN/m^2)	(ft/min)	(m/s)	$\frac{\text{lb-ft}}{\text{in.}^2\text{-min}}$	$\frac{\text{MNm}}{\text{m}^2\text{-sec}}$	(10^{-4} in.)	(µm)	(10^{-8} in. ft^{-1})	(10^{-9} m/m)	10^{-17} m^3/Nm	
CID-201-8x-1													
1,505	90.3	6,000	41.4	3	0.015	18,000	0.63	15.0	38.1	33.22	27.67	67.9	0.21
91	5.5	12,000	82.7	3	0.015	36,000	1.26	a/	-	-	-	-	0.15
SP-1 (10x)													
0.1	0.01	15,000	103.4	3	0.015	45,000	1.58	a/	-	-	-	-	--
CID-101-L-3													
600	61.7	6,000	41.4	3	0.015	18,000	0.63	a/	-	-	-	-	0.21
2	0.1	6,000	41.4	3	0.015	18,000	0.63	a/	-	-		-	-
CID-101-L-3													
1,446	86.8	6,000	41.4	3	0.015	18,000	0.63	10.3	26.2	23.74	19.78	48.6	0.10
4	0.2	12,000	82.7	3	0.015	36,000	1.26	a/	-	-	-	-	-
CID-121-1 (3x)													
1	0.1	15,000	82.7	3	0.015	-	-	a/	-	-	-	-	-

Note: CID-101-L-2 and -3 specimens contain 31% (vol.) graphite fibers (3/4 in. long; 0.019 m) + MoS_2 + Sb_2O_3 in a CPR matrix, CID-201-1 (8x) contains 44.4% (vol.) graphite fibers (T-50) + MoS_2 + Sb_2O_3 in a CPR matrix; SP-1 (10x) contains 59.1% (vol.) graphite fibers (T-50) in a CPR matrix; CID-121-1 contains graphite and BCM powders plus graphite fibers in a CPR matrix.

a/ Test was terminated early because sample crushed during the test; wear measurements are not meaningful.

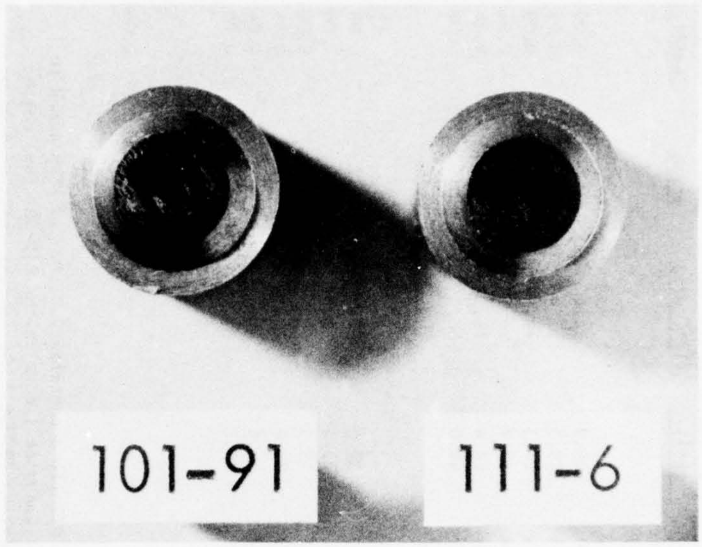

Figure 24 - Photograph of Tapered Specimens, CID-101-91 and CID-111-6 After Being Tested on the Oscillatory Slider at 27,450 psi (189.3 MN/m^2) and 3 fpm (0.015 m/s)

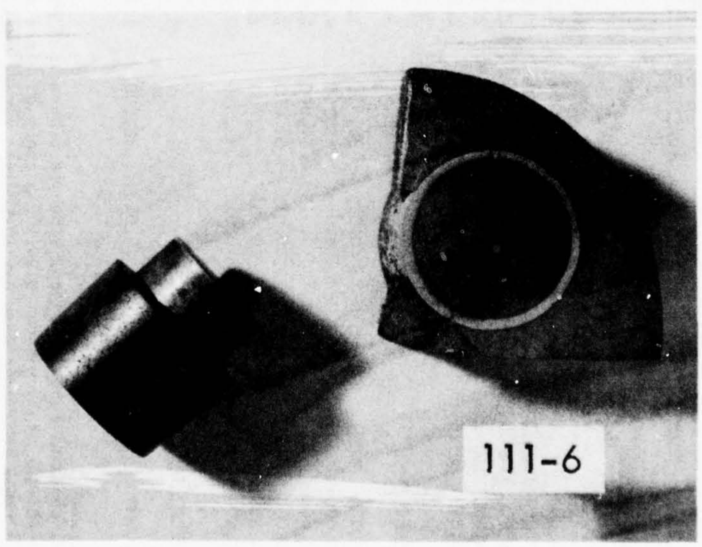

Figure 25 - Photograph of Portions of the CID-111-6 Composite Slug Showing: (1) On the Left, the Steel Cylindrical Housing Partially Pressed Out of the Composite in Which it was Formed and (2) On the Right, a Journal Bearing Housing Filled with the Composite and Not Yet Completely Removed From the Composite Slug in Which it was Formed

TABLE XIX

OSCILLATORY SLIDER FRICTION AND WEAR DATA FOR TAPERED COMPOSITE SPECIMENS FORMED IN STEEL SLEEVES

Running Time (min)	Running Time (ks)	Load (psi)	Load (MN/m^2)	Speed (ft/min)	Speed (m/s)	PV $\frac{lb\text{-}ft}{in.^2\text{-}min}$	PV $\frac{MNm}{m^2\text{-}sec}$	Wear (10^{-4} in.)	Wear (μm)	Wear Factor (10^{-8} in. ft^{-1})	Wear Factor (10^{-9} m/m)	Wear Factor 10^{-17} m^3/Nm	Average Friction Coefficient
CID-111-6 (Uncarbonized)													
197	11.8	12,000	82.7	3.0	0.015	36,000	1.26	1.0	2.54	16.9	14.1	17.4	0.06
180	10.8	15,000	103.4	3.0	0.015	45,000	1.58	1.0	2.54	18.5	15.4	15.2	0.05
205	12.3	18,000	124.1	3.0	0.015	54,000	1.89	1.0	2.54	16.3	13.6	11.1	0.05
188	11.3	21,000	144.8	3.0	0.015	63,000	2.21	1.0	2.54	17.7	14.7	10.3	0.04
181	10.9	24,000	165.5	3.0	0.015	72,000	2.52	1.0	2.54	18.4	15.3	9.39	0.04
580	34.8	27,450	189.3	3.0	0.015	82,350	2.88	8.0	20.3	46.0	38.3	20.5	0.04
CID-101-91 (Uncarbonized)													
1,456	87.4	12,000	82.7	3.0	0.015	36,000	1.26	12.0	30.5	27.5	22.9	28.1	0.08
1,440	86.4	15,000	103.4	3.0	0.015	45,000	1.58	11.0	27.9	25.5	21.2	20.8	0.06
180	10.8	18,000	124.1	3.0	0.015	54,000	1.89	1.0	2.54	18.5	15.4	12.6	0.06
202	12.1	21,000	144.8	3.0	0.015	63,000	2.21	2.0	5.08	33.0	27.5	19.3	0.05
180	10.8	24,000	165.5	3.0	0.015	72,000	2.52	3.0	7.62	55.6	46.3	28.4	0.04
509	30.5	27,450	189.3	3.0	0.015	82,350	2.88	6.0	15.2	39.3	32.7	17.6	0.04
CID-1101-5 (Uncarbonized)													
1,033	62.0	12,000	82.7	3.0	0.015	36,000	1.26	a/	-	a/	-	-	0.06

Note: CID-101-91 contains MoS_2, Sb_2O_3 and graphite fibers in a phenolic resin matrix; CID-111-3 contains 2.0% (vol.) PTFE added to the CID-101 (6x) composition; CID-1101-5 contains glass fibers substituted for graphite fibers in the CID-101 (6x) composition. These specimens were not carbonized. Test sample size: 0.25 in. diameter (0.00635 m). Stroke length: 1.0 in. (0.0254 m).

a/ Test was terminated early because sample crushed during the test; wear measurements are not meaningful.

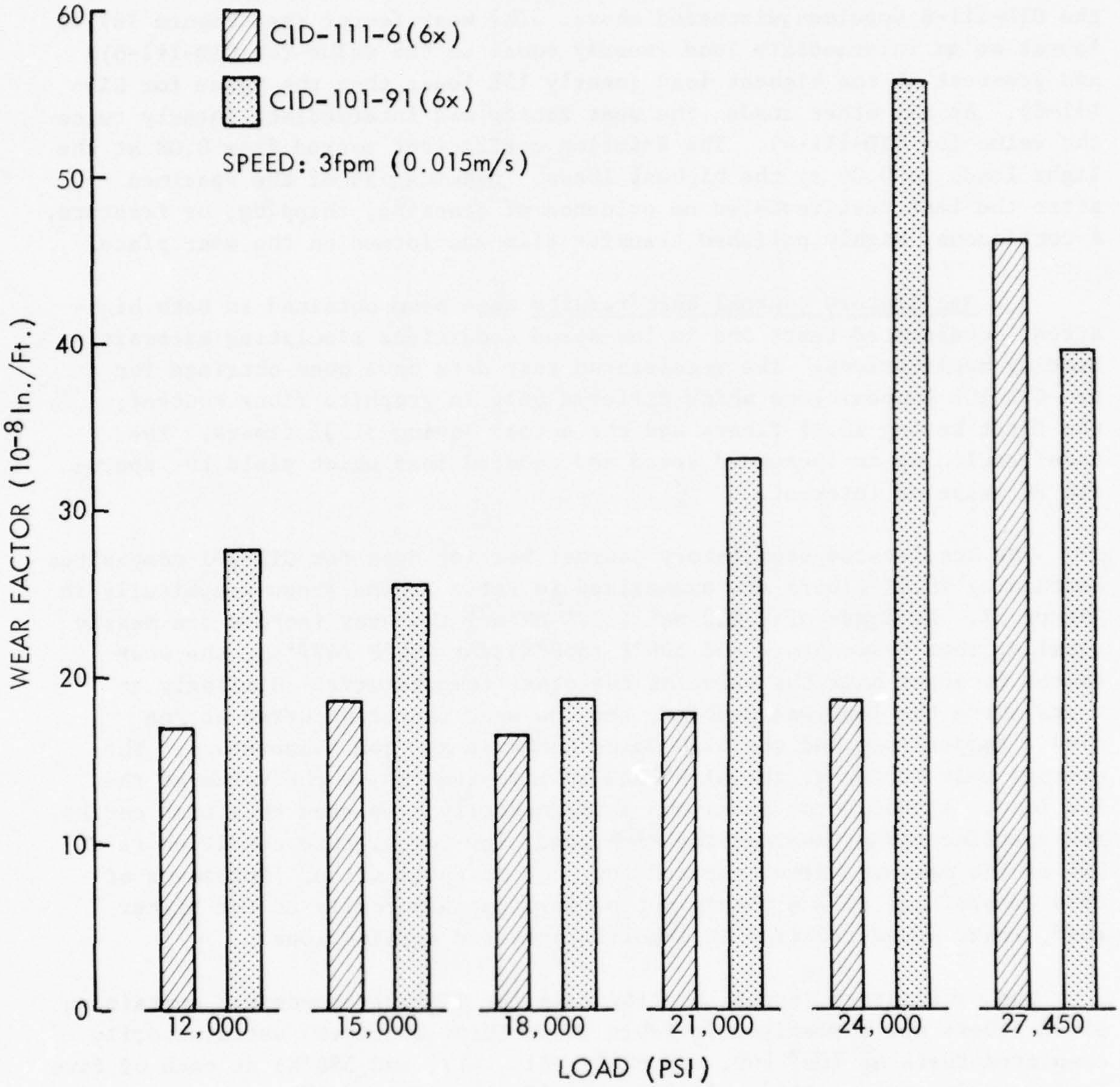

Figure 26 - Bar Graph Showing Wear Factor Versus Load for Uncarbonized CID-111 (6x) and CID-101 (6x) Composites Which Were Machined With a 45 Degree Taper at the Edge of the Test Surface to the Constraining, Cylindrical Steel Wall

b. CID-101-91 composite specimens contain $MoS_2 + Sb_2O_3$ + graphite fibers in a phenolic resin matrix. The data obtained in oscillatory slider tests with these sheathed, tapered, uncarbonized specimens are also summarized in Table XIX. The same load and speed conditions were used as with the CID-111-6 specimen discussed above. The wear factor (see Figure 26) is lowest at an intermediate load (nearly equal to the value for CID-111-6) and greatest at the highest load (nearly 15% lower than the value for CID-111-6). At all other loads, the wear factor was intermediate (nearly twice the value for CID-111-6). The friction coefficient ranged from 0.08 at the light loads to 0.04 at the highest loads. Examination of the specimen after the last test revealed no evidence of cracking, chipping, or fracture. A continuous, highly polished transfer film was formed on the wear plate.

3. Oscillatory journal test results have been obtained in both high-speed, accelerated tests and in low-speed conditions simulating aircraft bearing applications. The accelerated test data have been obtained for two CID-101 compositions which differed only in graphite fiber content; the first having 18.6% fibers and the second having 31.3% fibers. The acceleration is in increased speed and reduced load which yield the specific PV value of interest.

The accelerated oscillatory journal bearing data for CID-101 composites containing 18.6% fibers are summarized in Table XX and shown graphically in Figure 27. At loads of 2,000 psi (13.8 MN/m^2) the wear factors are nearly equal at room temperature and 600°F (588°K); at 400°F (477°K), the wear factor is about half the value at the other temperatures. Similarly in tests where the load was doubled, the low wear factor occurred at the middle temperature and the high value occurred at room temperature. The average wear factor at the high load is more than twice the value at the low load. Although the specimens satisfactorily completed this test series, the specific radial wear at the high-load, low-temperature condition is at 80% of the maximum value proposed for such an application. Specimens of this composition will probably not perform satisfactorily at the higher load, lower speed required in specific proposed applications.

The oscillatory journal bearing data for CID-101 composites containing 31.3% fibers are summarized in Table XXI. These specimens satisfactorily completed tests at 100, 400, and 600°F (311, 477, and 588°K) at each of five loads ranging from 2,000 to 10,000 psi (13.8 to 68.9 MN/m^2). The average radial wear in most tests was less than 1.0 μin/ft of sliding (8.3×10^{-8} m/m). A single, room-temperature test at 12,000 psi (82.7 MN/m^2) resulted in rapid failure of the composite bearing. The wear factor is depicted graphically as a function of load in Figure 28. This composite bearing material with 31.3% fibers has successfully completed the accelerated test program for oscillatory journal bearings. The high load of 10,000 psi (69 MN/m^2) and average speed of 2.18 fpm (0.011 m/s) results in a PV value slightly greater than the proposed value of 20,000 lb-ft/in^2-min (0.70 MNm/m^2s).

TABLE XX

ACCELERATED OSCILLATORY JOURNAL BEARING TEST RESULTS FOR CID-101 (3x) COMPOSITES

Composite Number	Test Time (hr)	Test Time (ks)	Number of Test Cycles	Load (psi)	Load MN/m^2	Test Temp. (°F)	Test Temp. (°K)	Wear (10^{-4} in.)	Wear (μm)	Wear Factor (10^{-8} in/ft)	Wear Factor (10^{-9} m/m)	Wear Factor (10^{-15} m^3/Nm)
101-69 (3x)	5.17	18.6	31,000	2,000	13.79	100	311	14.0	35.6	207	172	12.5
101-69 (3x)	4.17	15.0	25,000	2,000	13.79	400	477	4.5	11.4	83	69	4.96
101-69 (3x)	4.17	15.0	25,000	2,000	13.79	600	588	9.5	24.1	174	145	10.5
101-69 (3x)	4.28	15.4	25,660	4,000	27.58	100	311	40.0	101.6	715	595	21.6
101-69 (3x)	4.17	15.0	25,000	4,000	27.58	400	477	8.0	20.3	147	122	4.42
101-69 (3x)	4.17	15.0	25,000	4,000	27.58	600	588	18.5	47.0	339	282	10.2

Note: Specimen prepared with MoS_2 + Sb_2O_3 + graphite fibers in a phenolic resin matrix. The fiber content is 18.6% (vol.). Specimens carbonized at 400°C.

Test Conditions: Test device - Oscillatory journal (± 15 degrees, 60 degrees travel per cycle).
Journal diameter - 0.500 in. (0.0127 m).
Speed - 100 cpm (1.67 cps); 2.18 fpm (0.0111 m/s).

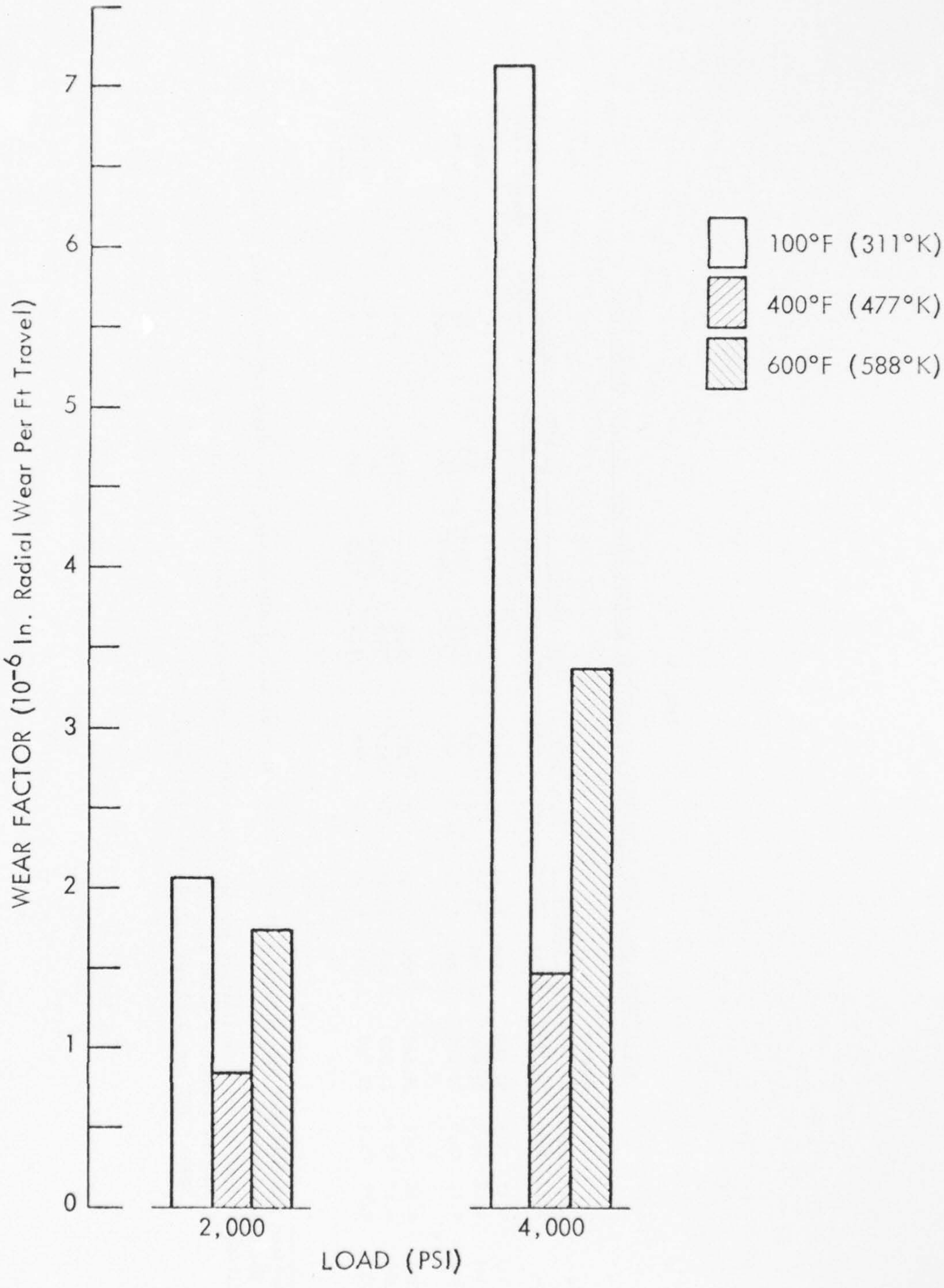

Figure 27 - Bar Graph Showing Wear Factor Versus Load for CID-101 (3x) Composites in Accelerated Oscillatory Journal Tests

TABLE XXI

ACCELERATED OSCILLATORY JOURNAL BEARING TEST RESULTS FOR CID-101 (6x) COMPOSITES

Composite Number	Test Time (hr)	Test Time (ks)	Number of Test Cycles	Load (psi)	Load MN/m^2	Test Temp. (°F)	Test Temp. (°K)	Wear (10^{-4} in.)	Wear (μm)	Wear Factor (10^{-8} in/ft)	Wear Factor (10^{-9} m/m)	Wear Factor (10^{-15} m^3/nM)
101-82 (6x)	4.42	15.9	26,550	2,000	13.79	100	311	8.5	21.6	147	122	8.88
101-82 (6x)	4.38	15.8	26,270	2,000	13.79	400	477	4.0	10.2	70	58	4.22
101-82 (6x)	4.18	15.1	25,100	2,000	13.79	600	588	4.0	10.2	73	61	4.41
101-82 (6x)	4.20	15.1	25,200	4,000	27.58	100	311	11.5	29.2	209	174	6.32
101-82 (6x)	4.37	15.7	26,200	4,000	27.58	400	477	1.0	2.5	18	15	0.520
101-82 (6x)	4.17	15.0	25,000	4,000	27.58	600	588	1.0	2.5	18	15	0.544
101-82 (6x)	4.17	15.0	25,000	6,000	41.37	100	311	4.0	10.2	73	61	1.48
101-82 (6x)	4.17	15.0	25,000	6,000	41.37	400	477	2.0	5.1	37	31	0.741
101-82 (6x)	4.17	15.0	25,000	6,000	41.37	600	588	4.0	10.2	73	61	1.48
101-82 (6x)	4.17	15.0	25,000	8,000	55.16	100	311	2.0	5.1	37	31	0.555
101-82 (6x)	4.17	15.0	25,000	8,000	55.16	400	477	6.2	15.7	114	95	1.71
101-82 (6x)	4.17	15.0	25,000	8,000	55.16	600	588	5.0	12.7	92	77	1.38
101-82 (6x)	4.22	15.2	25,330	10,000	68.95	100	311	2.5	6.4	45	37	0.550
101-82 (6x)	4.22	15.2	25,330	10,000	68.95	100	311	2.5	6.4	45	37	0.550
101-82 (6x)	4.18	15.0	25,100	10,000	68.95	400	477	3.5	8.9	64	53	0.775
101-82 (6x)	4.20	15.1	25,200	10,000	68.95	600	588	28.0	71.1	509	424	6.15
101-82 (6x)	0.08	0.3	490	12,000	82.74	100	311	a/	-	-	-	-

Note: Specimen prepared with MoS_2 + Sb_2O_3 + graphite fibers in a phenolic resin matrix. The fiber content is 31.3% (vol.). Specimens carbonized at 400°C.

Test Conditions: Test device - Oscillatory journal (± 15 degrees, 60 degrees travel per cycle).
Journal diameter - 0.500 in. (0.0127 m).
Speed - 100 cpm (1.67 cps); 2.18 fpm (0.0111 m/s).

a/ Test was terminated early because specimen crushed during the test; wear measurements are not meaningful.

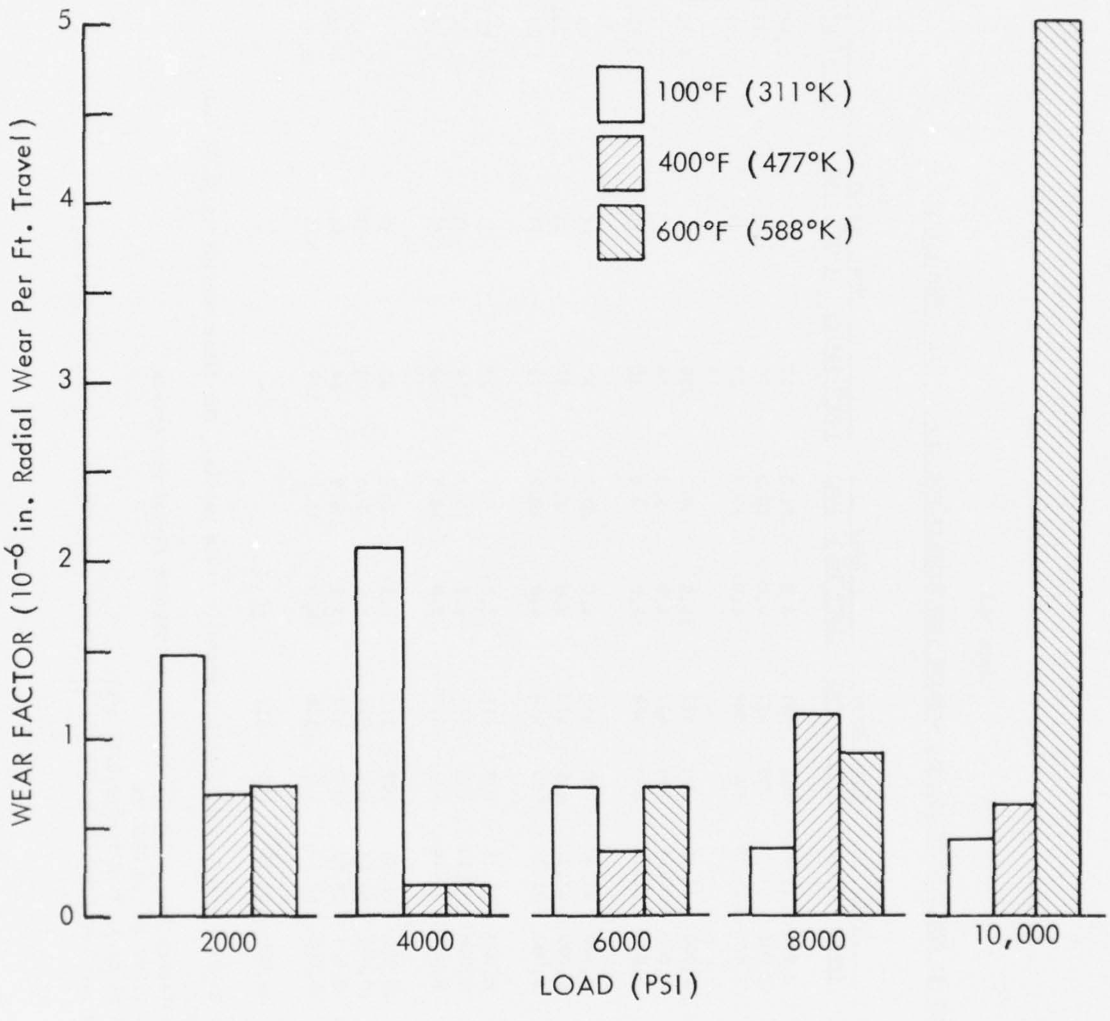

Figure 28 - Bar Graph Showing Wear Factor Versus Load for CID-101 (6x) Composites in Accelerated, Oscillatory Journal Tests

The low-speed oscillatory journal bearing data have been obtained for two types of composites. One of the composites is the same as was investigated in the accelerated tests discussed above (CID-101 with 18.6% fibers (3x)). The second composite, CID-111, contained 31% fibers and 2% PTFE powder. The data for a carbonized specimen of the CID-101 (3x) composite are shown in Table XXII and in Figure 29. This specimen withstood loads up to 8,000 psi (55.16 MN/m^2) in room temperature tests. The wear factor was low and each of the three lower loads and then increased significantly at the last load. Examination of the bearing after the last test revealed that excessive wear had occurred at one edge, indicating a misalignment of load. However, an average wear measurement was made and further testing of this composite was terminated.

The low-speed oscillatory journal bearing test data for an uncarbonized specimen of the CID-111 (6x) composite are also summarized in Table XXII and in Figure 29. Low wear was measured at a load of 6,000 psi (41.37 MN/m^2). However, at a load of 8,000 psi (55.16 MN/m^2) the specimen crushed in less than 2 hr of testing at room temperature. Again, the load appeared to be misaligned on the test bearing. Repeated efforts to alleviate this problem on other test bearings were unsuccessful with this test device.

TABLE XXII

LOW-SPEED OSCILLATORY JOURNAL BEARING TEST RESULTS FOR CID-101 (3x) AND CID-111 (6x) COMPOSITES

Composite	Test Time		Number of Test	Load		Test Temp.		Wear		Wear Factor		
Number	(hr)	(ks)	Cycles	(psi)	MN/m^2	(°F)	(°K)	(10^{-4} in.)	(μm)	(10^{-8} in/ft)	(10^{-9} m/m)	(10^{-15} m^3/Nm)
Carbonized Specimens												
101-70 (3x)	2.18	7.86	1,442	2,000	13.79	100	311	2.0	5.1	612	510	38.6
101-70 (3x)	26.0	93.5	17,135	4,000	27.58	100	311	13.5	34.3	346	288	10.9
101-70 (3x)	23.0	83.0	15,211	6,000	41.37	100	311	8.5	21.6	246	205	5.16
101-70 (3x)	16.8	60.4	11,082	8,000a/	55.16	100	311	52.0a/	132.0	2,063a/	1,719	32.5
Uncarbonized Specimens												
111-6 (6x)	19.6	70.5	12,930	6,000	41.37	100	311	2.5	6.4	85	21.9	1.8
111-6 (6x)	1.9	6.7	1,233	8,000	55.16	100	311	a/	-	a/	-	-

Note: Specimens prepared with MoS_2 + Sb_2O_3 + graphite fibers in a phenolic resin matrix; 2% (vol.) PTFE powder was added to the CID-111 specimen during formulation. The fiber content of the 101-70 specimen is 18.6% and for the 111-6 specimen is 31.3% (vol.). Specimen 101-70 was carbonized at 400°C; specimen 111-6 was uncarbonized.

Test Conditions: Test device - Oscillatory journal (± 15 degrees; 60 degrees travel per cycle).
Journal diameter - 0.500 in. (0.0127 m).
Speed - 11 cpm (0.25 fpm; 0.00122 m/s).
Temperature - no heat added.

a/ Test was terminated early because specimen was partially crushed during the test; wear measurements are questionable because of misalignment at the end of the test and the applied load had decreased to approximately half the original value.

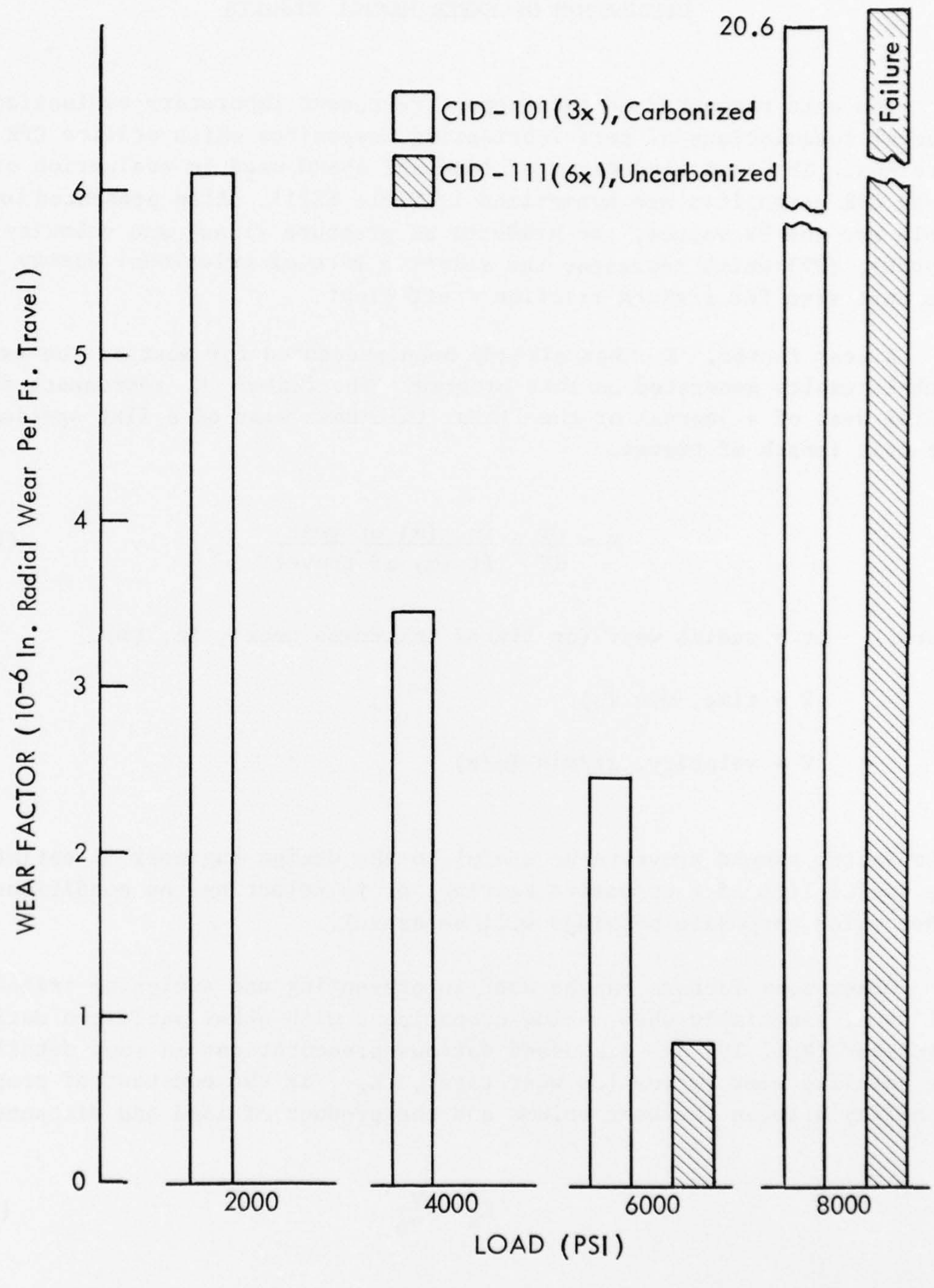

Figure 29 - Bar Graph Showing Wear Factor Versus Load for Two Composites in Low Speed Oscillatory Journal Tests

IV.

DISCUSSION OF EXPERIMENTAL RESULTS

The data presented in this report represent laboratory evaluation of several formulations of self-lubricating composites which utilize CPR matrices. The test conditions of load and speed used in evaluation of these CPR composites are summarized in Table XXIII. Also presented in the table are the PV values, the products of pressure (load) and velocity (speed), (PV) which represent the relative rate of frictional energy input per unit area for a given friction coefficient.

A wear factor, K , has already been presented for most of the experimental results generated on this program. The factor K represents the radial wear of a journal or the linear thickness wear of a flat specimen per unit length of travel.

$$K = \frac{\Delta r}{TV} = \frac{\text{in. (m) of wear}}{\text{ft (m) of travel}} \qquad (1)$$

where Δr = radial wear (or linear thickness wear), in. (m)

T = time, min (s)

V = velocity, ft/min (m/s)

This factor should prove to be useful to the design engineer in estimating the useful life of a composite bearing, or in selecting the conditions under which composite bearings will be useful.

Other wear factors can be used in presenting and analyzing tribological data, especially when making comparisons with other published data. Lancaster (Ref. 19) has discussed various presentations in some detail. The specific wear factor (or wear rate), K_s , is the constant of proportionality between the wear volume and the product of load and distance.

$$K_s = \frac{v}{Wd} \qquad (2)$$

where, in SI units: v = wear volume (m^3)

W = load (Newton)

d = sliding distance (m)

TABLE XXIII

PV VALUES FOR VARIOUS TEST CONDITIONS

A. Oscillatory Slider Tests (English Units)

Load (psi)	Speed (fpm):	PV $\left(\frac{\text{lb-ft}}{\text{in}^2\text{-min}}\right)$ at Various Speeds				
		3	9	12	24	36
1,500		-	-	18,000	36,000	54,000
3,000		-	-	36,000	72,000	108,000
6,000		18,000	54,000	-	-	-
9,600		28,000	86,400	-	-	-
12,000		36,000	108,000	-	-	-
15,000		45,000	-	-	-	-
18,000		54,000	-	-	-	-
21,000		63,000	-	-	-	-
24,000		72,000	-	-	-	-
27,450		82,350	-	-	-	-

B. Oscillatory Slider Tests (SI Units)

Load (MN/m^2)	Speed (m/s):	PV $\left(\frac{\text{MNm}}{\text{m}^2\text{-sec}}\right)$ at Various Speeds				
		0.015	0.046	0.061	0.122	0.183
10.3		-	-	0.63	1.26	1.89
20.7		-	-	1.26	2.52	3.78
41.4		0.63	1.89	-	-	-
66.2		1.01	3.03	-	-	-
82.7		1.26	3.78	-	-	-
103.4		1.58	-	-	-	-
124.1		1.89	-	-	-	-
144.8		2.21	-	-	-	-
165.5		2.52	-	-	-	-
189.3		2.88	-	-	-	-

TABLE XXIII (Concluded)

C. Oscillatory Journal Tests (English Units)

Load (psi)	Speed (fpm):	PV $\left(\frac{\text{lb-ft}}{\text{in}^2\text{-min}}\right)$ at Various Speeds 0.25	2.18
2,000		500	4,360
4,000		1,000	8,720
6,000		1,500	13,080
8,000		2,000	17,440
10,000		2,500	21,800
12,000		3,000	26,160

D. Oscillatory Journal Tests (SI Units)

Load (MN/m^2)	Speed (m/s):	PV $\left(\frac{\text{MNm}}{\text{m}^2\text{-sec}}\right)$ at Various Speeds 0.00122	0.0111
13.79		0.0168	0.153
27.58		0.0336	0.306
41.37		0.0505	0.459
55.16		0.0673	0.612
68.95		0.0841	0.765
82.74		0.1009	0.918

In cases where a linear wear factor, K_ℓ , is of most concern, as in journal-bearing applications, one can utilize the approximation that

$$v = rA \tag{2}$$

where r = radial wear (m)

A = projected area of contact (m^2)

Upon substitution for v and using the product of velocity, V (m/s) , and time, t (s) , for distance:

$$K_\ell = \frac{r}{W/A \cdot Vt} = \frac{r}{PVt} \tag{3}$$

The wear factor that has been presented and discussed earlier in the report for the data generated on this program is the linear wear factor, K , which represents the simple relationship of linear wear per distance traveled. However, the other two wear factors, K_ℓ and K_s have been calculated for comparison purposes using representative oscillatory-slider data, as shown in Table XXIV, and oscillatory journal data as shown in Table XXV. Also presented in those tables are typical wear factors found in the literature for some materials. Interesting comparisons can be made of the wear factors of other materials to those of the CPR composites.

The data shown in Table XXIV for six CPR composites which have been carbonized at 400°C (673°K) were obtained at room temperature on the oscillatory slider and represent only portions of the data presented in the previous report section. The data points were selected to include a low PV value at a low load, a high PV value at a high load and one high and one low PV value at intermediate loads.

The two specimens which contained only 18% graphite fibers (CID-101 (3x) and CID-103 (3x)) both failed at the high load, but do exhibit low wear factors at the lower loads. Two of the specimens which contain 31% graphite fibers (CID-101 (6x) and CID-111-3 (6x)) withstood the high test loads shown in Table XVII and exhibited low wear factors at those conditions. Another specimen which contained 31% fibers (CID-103 (6x)) exhibited low friction and wear until failure at the high load. The one specimen which contained 38% fibers (CID-101 (8x)) withstood all test loads, exhibiting low wear factors and friction coefficients.

TABLE XXIV

COMPARATIVE FRICTION AND WEAR DATA FROM SCREENING TESTS FOR CPR AND OTHER COMPOSITES

Material[a]	Type[b] of Test	Temp. (°K)	Load (MN/m^2)	Speed (m/s)	PV (MNm/m^{2}s)	Wear Factor, K_s (10^{-17} m^3/Nm)	Friction Coefficient	Reference[c]
CID-101 (3x)	FF,O	323	10.3	0.061	0.63	28.3	0.10	A
CID-101 (3x)	FF,O	323	20.7	0.183	3.78	4.72	0.04	A
CID-101 (3x)	FF,O	323	41.4	0.015	0.63	33.2	0.08	A
CID-101 (3x)	FF,O	323	82.7	0.046	3.78	failed	-	A
CID-101 (6x)	FF,O	323	10.3	0.061	0.63	22.3	0.15	A
CID-101 (6x)	FF,O	323	20.7	0.183	3.78	3.6	0.05	A
CID-101 (6x)	FF,O	323	41.4	0.015	0.63	20.2	0.12	A
CID-101 (6x)	FF,O	323	82.7	0.046	3.78	10.2	0.06	A
CID-101 (8x)	FF,O	323	10.3	0.061	0.63	-	-	A
CID-101 (8x)	FF,O	323	20.7	0.183	3.78	-	-	A
CID-101 (8x)	FF,O	323	41.4	0.015	0.63	31.3	0.09	A
CID-101 (8x)	FF,O	323	82.7	0.046	3.78	4.7	0.03	A
CID-103 (3x)	FF,O	323	10.3	0.061	0.63	34.5	0.15	A
CID-103 (3x)	FF,O	323	20.7	0.183	3.78	9.23	0.04	A
CID-103 (3x)	FF,O	323	41.4	0.015	0.63	failed	-	A
CID-103 (3x)	FF,O	323	82.7	0.046	3.78	failed	-	A
CID-103 (6x)	FF,O	323	10.3	0.061	0.63	79.4	0.22	A
CID-103 (6x)	FF,O	323	20.7	0.183	3.78	14.5	0.06	A
CID-103 (6x)	FF,O	323	41.4	0.015	0.63	23.7	0.08	A
CID-103 (6x)	FF,O	323	82.7	0.046	3.78	failed	-	A
CID-111 (6x)	FF,O	323	10.3	0.061	0.63	-	-	A
CID-111 (6x)	FF,O	323	20.7	0.183	3.78	-	-	A
CID-111 (6x)	FF,O	323	41.4	0.015	0.63	15.4	0.18	A
CID-111 (6x)	FF,O	323	82.7	0.046	3.78	3.89	0.05	A
CID-111 (6x)	FF,O-C	323	165.5	0.015	2.52	9.39	0.04	A
CID-101 (6x)	FF,O-C	323	165.5	0.015	2.52	28.4	0.04	A
PI+GF-I (R)	CC,U					4.4	0.23	B
E+GF-II (R)	CC,U					82.0	0.57	B
PP+GF-II (P)	CC,U					75.0	0.45	B
V+GF-I (Fe)	CC,U	323	(11.7N)[c]	0.53	c/	85.0	-	C
V+GF-I (Cr)	CC,U	323	(11.7N)[c]	0.53	c/	48.0	0.20	C
V+GF-I (Fe)	CC,U	473	(11.7N)[c]	0.53	c/	850.0	-	C
V+GF-I (Cr)	CC,U	473	(11.7N)[c]	0.53	c/	600.0	0.10	C
V+GF-I (Fe)	CC,U	573	(11.7N)[c]	0.53	c/	2,400.0	-	C
V+GF-I (Cr)	CC,U	573	(11.7N)[c]	0.53	c/	970.0	0.10	C
V+GF-II (Fe)	CC,U	323	(11.7N)[c]	0.53	c/	103.0	-	C
V+GF-II (Cr)	CC,U	323	(11.7N)[c]	0.53	c/	85.0	0.18	C
V+GF-II (Fe)	CC,U	473	(11.7N)[c]	0.53	c/	850.0	-	C
V+GF-II (Cr)	CC,U	473	(11.7N)[c]	0.53	c/	250.0	0.10	C

TABLE XXIV (Concluded)

Material[a/]	Type[b/] of Test	Temp. (°K)	Load (MN/m^2)	Speed (m/s)	PV (MNm/m^2s)	Wear Factor, K_s (10^{-17} m^3/Nm)	Friction Coefficient	Reference[c/]
V+GF-II (Fe)	CC,U	573	(11.7N)[c/]	0.53	c/	2,400.0	-	C
V+GF-II (Cr)	CC,U	573	(11.7N)[c/]	0.53	c/	1,200.0	0.18	C
PI+GF+CdI_2	CC,U	323	(11.7N)[c/]	0.53	c/	9.7	-	C
PI+GF+CdI_2	CC,U	473	(11.7N)[c/]	0.53	c/	42.0	-	C
PI+GF+CdI_2	CC,U	573	(11.7N)[c/]	0.53	c/	96.0	-	C
PM-103	CC,U	300	2.75	0.36	0.99	186.0	0.37-0.03	D
PM-103	CC,U	300	5.17	0.36	1.86	68.7	0.12-0.03	D
PM-103	CC,U	300	10.3	0.36	3.71	25.7	0.15-0.05	D
PM-103	CC,U	300	15.5	0.36	5.58	7.9	0.25-0.03	D
PM-103	CC,U	300	20.7	0.36	7.45	10.1	0.16-0.03	D

a/ Material Composition

CID-101: MoS_2 + Sb_2O_3 + graphite fibers in a carbonized phenolic resin (CPR) matrix; 3x = 18%, 6x = 31%, 8x = 38% fibers.

CID-103: MoS_2 + ZnO + graphite fibers in a CPR matrix; 3x = 18%, 6x = 31% fibers.

CID-111-3 (6x): 2% tetrofluoroethylene powder added to CID-101 (6x) composition.

PI+GF-I (R): Polyimide resin matrix filled with Type I graphite fibers in a random orientation.

E+GF-II (R): Epoxy resin matrix filled with Type II graphite fibers in a random orientation.

PP+GF-II (P): Polyphenylene resin matrix for Type II graphite fibers oriented parallel to the sliding direction.

V+GF-I: Typical of various resin matrix composites with Type I graphite fibers mated against mild steel (Fe) or chrome plated steel (Cr).

V+GF-II: Type II graphite fibers used in above composites.

PI+GF+CdI: Polyimide resin matrix for graphite fibers and CdI_2.

b/ Type of Test:

FF,O - Flat specimen on flat steel mating surface in oscillatory motion.

FF,O-C - Flat end of cylindrical, uncarbonized specimens (tapered at edges to a constraining steel sleeve) sliding on flat steel mating surface in oscillatory motion.

CC,U - Cylindrical specimen on cylindrical mating surface, axes at 90 degrees, in unidirectional motion.

c/ Source:

A - This report, Section III.

B - J. P. Giltrow, See Ref. 7.

C - J. P. Giltrow, See Ref. 8.

D - Technical Bulletin, Pure Carbon Company.

Data are also shown in Table XXIV for two uncarbonized specimens, which were compression molded within constraining steel sleeves and machined at a 45 degree taper to form a flat, circular contact area, withstood loads of twice the value sustained by similar, unrestrained specimens. That these specimens exhibited low friction and wear characteristics under such high loads, indicates that these composites offer great potential for use where bearings are specifically designed to utilize their material properties to best advantage.

Additional data shown in Table XXIV were gleaned from the literature. These data, reported by Giltrow (Refs. 7-8), were collected in a different type of screening test device than used at MRI and this fact makes the data comparison subject to question. However, the wear trends with temperature and composition may still be valid for a comparative discussion.

The test configuration consisted of a cylindrical composite specimen (0.25 in. diameter; 0.00635 m) in contact with a rotating metal cylinder (4.0 in. diameter, 0.10 m). The load was 2.64 lb (11.7 N) and the unit loading changed during each test, as the wear progressed. However, it is estimated that the unit loading for most of those specimens reached a value less than 80 MN/m^2 within the first hour of the test. If that is true, then the unit loading would be comparable to the values used in the MRI tests over a substantial period of the test. However, it should be kept in mind that the unit loading would remain high much longer for specimens exhibiting a low wear factor than for those having a high wear factor.

The wear factor shown in Table XXIV for polyimide resin with Type I graphite fibers in random orientation is very low (4×10^{-17} m^3/Nm), equivalent to several CPR specimens tested at 20.7 MN/m^2 and 0.183 m/s. However, the friction coefficient is four to five times that of the CPR specimens. Other composites prepared with epoxy or polyethylene resin matrices and containing either Type I or Type II graphite fibers are listed in Table XXIV with room temperature wear factors 20 times that cited above. Data are also shown for composites prepared with various resin matrices which were tested at elevated temperatures wherein the mating material was either mild steel (Fe) or chrome plated steel (Cr). The wear factor is shown to increase by about a factor of 10 when the temperature is increased from 323°K to 475°K (122 to 400°F) and another factor of 1.5 to 3.0 when the temperature is increased to 573°K (570°F). In all cases the wear factor is significantly lower when chromium plated steel is used instead of mild steel as the mating surface.

Data are also shown in Table XXIV for composites of graphite fibers and CdI_2 powder in a polyimide matrix. The wear factors for these composites at 122°F (323°K) are double the value shown for room temperatures tests of a similar composite without the CdI_2. The wear factors for these composites also increase with temperature by a factor of four at 400°F (473°K) and a factor of 10 at 570°F (573°K).

The data shown in Table XXV include a summary of the oscillatory journal bearing data generated on this program as well as some similar data recently reported by Sliney (Ref. 20). The data for CID-101 (6x) composites indicate a general decrease in wear factor with increasing load at each temperature. Furthermore, the wear factors at 400 and 600°F (477 and 588°K) tend to be lower than those measured at 100°F (311°K). Comparison with data in Table XVII indicate that the wear factor is higher by a factor of 10 to 100 for these oscillatory journal test conditions than for oscillatory flat-on-flat bearing surfaces.

The data shown in Table XXV for CID-101 (3x) specimens, which contain 18% fibers, indicate a distinctly inferior performance in comparison with the CID-101 specimens which contain 31% fibers. The lowest wear factors for the CID-101 (3x) specimens were found at 400°F (477°K) and next lowest at 600°F (588°K). However, little difference was found between the two loads at those temperatures.

The data reported by Sliney (Ref. 20), which are included in Table XXV, indicate that wear-rates for graphite fiber filled polyimide composites are approximately the same as those of CID-101 (6x) composites. Sliney's data also indicate substantial reduction in wear rate for liners that are molded in place when compared to inserted liners that have been machined from composite blanks.

TABLE XXV

COMPARATIVE FRICTION AND WEAR DATA FROM OSCILLATORY JOURNAL TESTS FOR CPR AND OTHER COMPOSITES

Material[a]	Temp. (°K)	Load (MN/m^2)	Speed (m/s)	PV (MNm/m^2s)	Wear Factor, K_ℓ (10^{-17} m^3/Nm)	Friction Coefficient	Source[b]
CID-101 (6x)	311	13.8	0.011	0.15	888.0	-	A
CID-101 (6x)	311	27.6	0.011	0.31	635.0	-	A
CID-101 (6x)	311	41.4	0.011	0.46	148.0	0.12	A
CID-101 (6x)	311	55.2	0.011	0.61	55.7	-	A
CID-101 (6x)	311	69.0	0.011	0.76	55.9	0.07	A
CID-101 (6x)	477	13.8	0.011	0.15	424.0	-	A
CID-101 (6x)	477	27.6	0.011	0.31	52.1	-	A
CID-101 (6x)	477	41.4	0.011	0.46	74.2	-	A
CID-101 (6x)	477	55.2	0.011	0.61	171.0	-	A
CID-101 (6x)	477	69.0	0.011	0.76	77.5	-	A
CID-101 (6x)	588	13.8	0.011	0.15	445.0	-	A
CID-101 (6x)	588	27.6	0.011	0.31	54.6	-	A
CID-101 (6x)	588	41.4	0.011	0.46	148.0	-	A
CID-101 (6x)	588	55.2	0.011	0.61	139.0	-	A
CID-101 (6x)	588	69.0	0.011	0.76	615.0	-	A
CID-101 (3x)	311	13.8	0.011	0.15	1,250.0	-	A
CID-101 (3x)	311	27.6	0.011	0.31	2,160.0	0.08	A
CID-101 (3x)	477	13.8	0.011	0.15	498.0	-	A
CID-101 (3x)	477	27.6	0.011	0.31	443.0	-	A
CID-101 (3x)	588	13.8	0.011	0.15	1,050.0	-	A
CID-101 (3x)	588	27.6	0.011	0.31	1,030.0	-	A
CID-101 (3x)	311	13.8	0.0012	0.017	3,860.0	-	A
CID-101 (3x)	311	27.6	0.0012	0.034	1,090.0	-	A
CID-101 (3x)	311	41.4	0.0012	0.051	516.0	-	A
CID-101 (3x)	311	55.2	0.0012	0.084	3,250.0	-	A
CID-111 (6x)	311	41.4	0.0012	0.051	180.0	-	A
PI+GF (IL)	298	28.5			400.0	0.15	D
PI+GF (ML)	298	28.5			110.0	0.15	D
PI+GF (IL)	478	28.5			450.0	0.08	D
PI+GF (ML)	478	28.5			160.0	0.08	D
PI+GF (IL)	588	28.5			260.0	0.05	D
PI+GF (ML)	588	28.5			120.0	0.05	D

a/ Material Composition:

CID-101 (6x): MoS_2 + Sb_2O_3 + graphite fibers (31%) in a carbonized phenolic resin matrix.

CID-101 (3x): Substitute 18% for 31% fibers in above composition.

PI+GF (IL): Graphite fibers in a polyimide matrix; liner machined and inserted in metal sleeve.

PI+GF (ML): Same composition as above; liner molded directly in the metal sleeve.

b/ Source:

A - This report, Section III.

D - H. E. Sliney, see Ref. 20.

V.

CONCLUDING COMMENTS

1. CPR composites have been successfully prepared with as much as 59% (vol.) graphite fibers.

2. Compressive strength data for 97 separate specimens indicate that fiber content of 18 to 31% is beneficial in these composites. Uncarbonized composites are generally stronger in these tests than are the carbonized specimens. The addition of 2 to 4% PTFE (CID-111 composition) improves the compressive strength over that of the CID-101 composites (which are of similar composition without PTFE). The substitution of ZnO (CID-103) for Sb_2O_3 (CID-101) does not improve the composite strength. The use of longer graphite fibers (CID-101-L) results in no significant change in strength from composites utilizing short fibers (CID-101). Carbonizing of the composite while under pressure in the die generally results in lower compressive strength than is achieved by the very slow carbonizing rate of composites not under external pressure. The substitution of glass fibers (CID-1101) for graphite fibers (CID-101) does not significantly change the compressive strength. Comparison of values with those reported for some other self-lubricating composites with 600°F capabilities, reveals that some of the Molalloy compacts, which utilize a refractory metal matrix for MoS_2 and are compression molded at very high temperatures, exhibit compressive strengths three to six times as great as CPR composites. Other Molalloy compacts and some Vespel compacts, which utilize polyimide resin as a matrix for MoS_2, graphite or PTFE, are reported to have compressive strengths very similar to that measured for the better CPR composites.

3. Screening data obtained by oscillatory sliding of flat specimens shows improved load carrying capacity of specimens with increasing fiber content (from 0 to 31%). Little change in friction coefficient is noted with increased fiber content; the friction coefficient is usually between 0.04 and 0.10 and occasionally between 0.10 and 0.20.

4. Screening data have been obtained with especially prepared specimens of CID-101 and CID-111 composites at loads as high as 27,450 psi (189.3 MN/m^2) at an average speed of 3 fpm (0.015 m/s). The special preparation included compression molding within a constraining steel sleeve and 45 degrees tapering of the edges adjacent to the wear area. The special preparation features probably contributed to the doubling of the test load capacity of these composites over that achieved with flat, square composite specimens cemented directly to a steel plate.

5. The synergistic effect of Sb_2O_3 appears to be more beneficial than ZnO, even at the higher loads and lower speeds which have been included in current screening experiments.

6. Beneficial synergistic effects in both friction and wear have been shown in screening experiments by the addition of tetrafluoroethylene powders to composites containing MoS_2, Sb_2O_3, and graphite fibers in a carbonized phenolic resin matrix.

7. The friction coefficients of the better CPR composites, such as CID-101 and CID-111, are low over a wide range of loads, speeds, and temperatures in oscillatory motion. The coefficients are generally less than 0.20 at the light loads (1,500 psi; 10.3 MN/m^2) and less than 0.10 at the higher loads (12,000 psi; 82.7 MN/m^2). These friction coefficient values are acceptable for most applications of self-lubricating composites.

8. Journal bearing liners have been successfully molded and carbonized directly in metal housings.

9. Data from oscillatory journal bearing tests show satisfactory performance for CID-101 composites containing 31% fibers at loads up to 10,000 psi (69 MN/m^2), temperature to 600°F (588°K) and at speeds of 100 cpm (1.67 cps); the oscillation is $\pm$ 15 degrees with average linear speeds of 2.18 ppm (0.011 m/s).

10. At the present stage of development the CPR composites compare very favorably in terms of wear and friction coefficients to the better self-lubricating composites currently available.

11. Self-lubricating composites which utilize a matrix of carbonized phenolic resin tend to be brittle. This factor needs to be considered in the evaluation and use of CPR composites. The design of bearing housings to minimize edge stresses may be important in maximizing the performance of CPR composites.

12. Additional tribological data may be very useful in assessing the potential applications and limitations of CPR composites, especially bearing designs which minimize edge loading and which provide compressive preload in order to minimize edge chipping.

REFERENCES

1. Bowden, F. P., and D. Tabor, The Friction and Lubrication of Solids, Part II, Oxford Press (1964).

2. Flom, D. G., "Rolling Friction of Polymeric Materials, II, Thermoplastics," J. Appl. Phys., Vol. 32, No. 8, August 1961.

3. Vest, C. E., and B. W. Ward, Jr., "Evaluation of Space Lubricants Under Oscillatory and Slow Speed Rotary Motion," Lubr. Engrg, Vol. 24, No. 4, pp. 163-172, April 1968.

4. Lancaster, J. K., "The Effect of Carbon Fibre Reinforcement on the Friction and Wear of Polymers," Brit. J. Appl. Phys. (J. Phys. D), Sec. 2, Vol. 1, pp. 549-559 (1968).

5. Giltrow, J. P., and J. K. Lancaster, "The Friction and Wear of Carbon Fiber-Reinforced PTFE," Proceedings of the AFML-MRI Conference on Solid Lubricants, pp. 305-331, AFML-TR-70-127, September 9-11, 1969.

6. Lancaster, J. K., "Composite Self-Lubricating Bearing Materials," Proc. Instn. Mech. Engrs., Vol. 182, Part 1 (1967-68).

7. Giltrow, J. P., "A Design Philosophy for Carbon Fibre Reinforced Sliding Components," Tribology, pp. 21-28, February 1971.

8. Giltrow, J. P., "The Influence of Temperature on the Wear of Carbon Fiber Reinforced Resins," ASLE Trans., Vol. 16, No. 2, pp. 83-90, April 1973.

9. Theberge, J. E., and B. Arkles, "Wear Characteristics of Carbon Fiber Reinforced Thermoplastics," Lubr. Engrg., Vol. 30, No. 12, pp. 585-589, December 1974.

10. Campbell, M. E., and V. Hopkins, "Development and Evaluation of Lubricant Composites Based on Polyphenylene Sulfide," MRI Report No. SLTC-731 (1973).

11. Powers, T. E., "Molybdenum Disulfide in Nylon for Wear Resistance," Modern Plastics, June 1960.

12. Campbell, M. E., and J. W. VanWyk, "Development and Evaluation of Lubricant Composite Materials," Lubr. Engrg., Vol. 20, p. 463 (1964).

13. Hubbell, R. D., B. D. McConnell, and J. W. VanWyk, "Development of Solid Lubricant Compacts for Use in Ball Bearing Separators," Lubr. Engrg., Vol. 25, No. 1, January 1969.

14. Lavik, M. T., and R. D. Hubbell, "Partially Carbonized Organic Polymers as Matrices for Self-Lubricating Films and Composites," U.S. Letters Patent No. 3,847,825.

15. Hopkins, V., et al., "Improved High-Temperature Solid Film Lubricants," AFML-TR-71-61, Part I (April 1971), Part II (January 1972), Part III (June 1973), and Part IV (October 1974).

16. Lavik, M. T., and V. Hopkins, "Development of Self-Lubricating Composites Utilizing Carbonized Phenolic Matrix," AFML-TR-75-175, Part I (December 1975).

17. See, for example, Yamada, S., "A Review of Glasslike Carbons," DCIC Report 68-2 April 1968.

18. Lavik, M. T., R. D. Hubbell, and B. D. McConnell, "Oxide Interaction--A Concept for Improved Performance with Molybdenum Disulfide," Lubr. Engrg., Vol. 31, No. 1, January 1975.

19. Lancaster, J. K., "Dry Bearings: A Survey of Materials and Factors Affecting Their Performance," Tribology, pp. 219-251, December 1973.

20. Sliney, H. E., and T. P. Jacobson, "Performance of Graphite Fiber-Reinforced Polyimide Composites in Self-Aligning Plain Bearings to 315°C," paper presented at the ASLE 30th Annual Meeting, Atlanta, Georgia, Preprint No. 75 AM-2D-4, May 5-8, 1975.

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